AFIT/GEE/CEC/92S-3

A MODEL ACTION PLAN TO REDUCE THE USE AND RELEASE OF CFCs IN AIR-CONDITIONING AND REFRIGERATION SYSTEMS

THESIS

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THESIS

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Preface

The purpose of this thesis is to develop a model action plan (MAP) or methodology for reducing chlorofluorocarbons (CFCs) in air conditioning and refrigeration. The MAP provides a manager with a systematic method to identify available alternatives and provide relative cost data and analysis for those alternatives.

In writing this thesis, we would like to express our thanks to those who contributed their time and patience toward a successful completion. We are grateful to our faculty advisor, Captain Pedro Camejo, and the committee members Captains Jim Donaghue, David Herman, and Tracy Willcoxon for their direction, suggestions, and patience throughout the process. We also thank the Wright-Patterson base personnel and local businesses who provided valuable information. Finally, we wish to thank our families for their understanding and support through the trying times.

David W. Andrews Daniel P. Ellert-Beck

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Abstract

This study investigated methods to reduce the use and release of chlorofluorocarbon (CFC) refrigerants and evaluated alternatives to CFCs in air-conditioning and refrigeration systems. A life cycle cost (LCC) analysis formed the basis for evaluation. A literature review examined applicable CFC directives, containment methods, replacement refrigerants, and alternative processes. Current legislation requires that production and use of CFCs will be banned by the year 2000. CFC recovery and reuse is imperative during the phaseout period. No drop-in substitutes for CFCs have been found, but some hydrochlorofluorocarbon and hydrofluorocarbon compounds are viable in retrofit applications. The toxicity and flammability of ammonia make it too hazardous for most applications. Absorption cycle chillers present a suitable alternative; however, high initial costs made it unattractive in the LCC analysis.

The results of the LCC analysis showed that maintaining the existing CFC system was always the least costly alternative. When forced to replace a CFC reciprocating package unit, the best replacement was a non-CFC reciprocating unit. The most practical replacement for reciprocating chillers was a new reciprocating chiller for systems less than 150 tons, and screw chillers for systems 150 tons or larger. Retrofitting a centrifugal chiller was cost-effective if the system had been in service no more than 11 years for a 200-ton unit, 17 years for a 400-ton unit, and 18 years for a 1000-ton unit. Otherwise, 200-ton units should be replaced with screw chillers and 400 and 1000-ton units with centrifugal chillers.

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I. Introduction

General Issue

Chlorofluorocarbons (CFCs) are man-made molecules consisting entirely of chlorine, fluorine, and carbon atoms. CFCs are widely used as refrigerants in comfort cooling and cold storage refrigeration systems. Unfortunately, CFCs released into the atmosphere damage the Earth's protective ozone layer and contribute to global warming.

Researchers have found evidence linking CFCs with the approximate three-fold increase in concentration of chlorine in the stratosphere from 1950 to 1990 (3:45). CFC molecules are chemically inert and insoluble in water. Once released into the atmosphere, they can remain unchanged for well over one-hundred years. Ultra-violet radiation in the middle stratosphere eventually breaks-up the CFC molecules, thus freeing chlorine (45:622,624). The chlorine molecules released break down ozone through the following reactions (27:43):

$$Cl + O_3 \rightarrow ClO + O_2$$

$$ClO + O \rightarrow Cl + O_2$$

The chlorine molecule is not consumed in the reaction and is free to destroy more ozone molecules. Stratospheric depletion of ozone is a concern because the ozone absorbs the harmful short-wavelength ultraviolet radiation that can cause skin cancer in humans (32:430).

The increase in concentration of CFCs in the atmosphere also contributes to global warming. CFCs absorb infrared radiation emitting from the Earth's surface. Most climatologists predict an increase of three degrees centigrade in average global temperature by 2050 (45:627). The contribution by CFCs to global warming is significant because a molecule of CFC has on the order of 1,000 times more global warming potential than a molecule of carbon dioxide. However, global warming is not regarded as serious an environmental issue when compared to ozone depletion because the causes and effects are less well established (21:39,41).

The international community recognized these global environmental concerns and agreed to phase out the use of CFCs in a multi-national agreement known as the Montreal Protocol. The requirements of the Montreal Protocol were included in Title VI of the 1990 Clean Air Act Amendments.

Headquarters U.S. Air Force has drafted policies restricting purchase of ozone layer depleting substances, including CFCs. Non-CFC alternatives for air-conditioning and refrigeration systems must be implemented at Air Force bases.

Specific Problem

The purpose of this research is to develop a model action plan for a typical Air Force base to economically reduce the use and release of regulated CFCs in air-conditioning and refrigeration systems.

Research Objectives

The principle goal of this research is to develop a model action plan to effectively and economically replace existing CFC-based air-conditioning and refrigeration systems with non-CFC alternatives. The research objectives consist of answering the following investigative questions:

1. What requirements are imposed by the legislation, regulations, and policies concerning CFCs?

2. What containment methods and technologies exist to reduce or eliminate the release of CFC refrigerants?

3. What refrigerants are available as a substitute for CFCs in existing or new equipment?

4. What air-conditioning and refrigeration processes exist that eliminate the need for CFCs?

The final objective is to evaluate non-CFC alternatives and develop a model action plan for decision making.

Scope

The research focuses on air-conditioning and refrigeration systems which use CFCs and which may be found on a typical Air Force base. These systems include residential and commercial systems. Other industrial uses of CFCs as solvents, blowing agents, and fire suppression agents are not in the scope of the research.

The literature review examines four separate topics: directives, containment, refrigerant replacement, and alternative processes. Evaluation of advantages and disadvantages of the non-CFC strategies forms the basis of the model action plan.

Directives. The applicable legislation, regulations, and policies define the constraints of the model action plan. The literature review examines Air Force policies and regulations, legislation from other federal agencies, as well as policies from equipment manufacturers and refrigerant suppliers. Federal legislation provides pertinent information such as the timetable for CFC phaseout. The policies of refrigerant suppliers are also important since they influence the availability of CFCs and other refrigerants. Likewise, air conditioner manufacturers control the availability of suitable equipment for use with non-CFC refrigerants.

Containment. The Clean Air Act prohibits the intentional release of CFC refrigerants effective July 1, 1992 (52:2650). For this reason, research into current practices and technologies available for preventing the release of CFCs into the atmosphere is critical. Refrigerant recovery and the feasibility of recycling CFCs is included in this research effort.

Refrigerant Replacements. The research also considers the feasibility of using other refrigerants such as hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), and ammonia. HCFCs are less damaging to the ozone layer than CFCs (50:42). However, HCFCs are slated to be phased out by the year 2020 or earlier (28:52). HFCs have zero potential for ozone depletion because they lack chlorine molecules. Though they are not currently regulated, HFCs have a high potential for global warming and may one day be regulated (27:43). Therefore, HCFCs and HFCs may prove useful only as short term solutions.

Alternative Processes. An air-conditioning and refrigeration process which does not use CFCs is the absorption cycle. The research examines the advantages and disadvantages offered by this existing technology for potential replacement of current applications which use CFC refrigerants.

Definition of Terms

There are several categories of fluorocarbon compounds discussed in the research. Chlorofluorocarbon molecules consist entirely of chlorine, fluorine, and carbon atoms. When a hydrogen atom is bonded to the molecule in place of one of the chlorine atoms, the molecule is called a hydrochlorofluorocarbon, or HCFC. A hydrofluorocarbon, HFC, contains no chlorine and consists of hydrogen, fluorine, and carbon atoms.

Different CFC molecules are commonly referred to by a number system developed by DuPont which describes the chemical's formula (32:413). The number associated with a given fluorocarbon refrigerant, when added to 90, reveals the number of carbon, hydrogen, and fluorine atoms contained in the compound. Chlorine atoms make up the remaining available bond sites. For example, CFC-11, trichlorofluoromethane, which has the formula $CFCl_3$, has one atom of carbon, no hydrogen atoms, one fluorine atom, and three atoms of chlorine. Another example is CFC-12, dichlorodifluoromethane (CF_2Cl_2), which has one carbon atom, two fluorine atoms, and two chlorine atoms.

When fluorocarbons are used as refrigerants, they are often labeled with an R- prefix. For example, R-11 and R-22 represent CFC-11 and HCFC-22, respectively. Fluorocarbon refrigerants may also be known by their trade names, such as Freon-22 or Genetron-22. Table 1 contains a list of chemical names and formulas for refrigerants discussed in this report.

TABLE 1

CHEMICAL NAMES AND FORMULAS FOR SELECTED REFRIGERANTS

Refrigerant	Chemical Name	Chemical Formula
CFC-11	Trichlorofluoromethane	$CFCl_3$
CFC-12	Dichlorodifluoromethane	CF_2Cl_2
CFC-114	Dichlorotetrafluoroethane	$CCl_2F_2CClF_2$
CFC-115	Chloropentafluoroethane	CF_3CF_2Cl
HCFC-22	Chlorodifluoromethane	$CHClF_2$
HCFC-123	Dichlorotrifluoroethane	$CHCl_2CF_3$
HCFC-124	Chlorotetrafluoroethane	$CHClFCF_3$
HFC-134a	1,1,1,2-Tetrafluoroethane	CH_2FCF_3
HFC-152a	1,1-Difluoroethane	CH_3CHF_2
R-500	Blend of: CFC-12 (73.8%) HFC-152a (26.2%)	--
R-502	Blend of: CFC-115 (51.2%) HCFC-22 (48.8%)	--
R-717	Ammonia	NH_3

(19:12; 2:6; 21:39)

Overview

Following this introduction is a literature review providing background information for the model action plan. The literature review covers applicable legislation and policies, strategies for preventing the release of CFCs, refrigerant replacement for existing equipment, and alternative non-CFC processes that may be implemented. Conclusions of the literature review provide the information to create the framework of the model action plan. The next chapter also includes the model action plan overview, assumptions, and context in which it will be used.

A description of the methodology used to evaluate the information and to develop the model action plan appears in Chapter III. Validation of the model action plan is also presented in Chapter III, while findings and analysis of the results are disclosed in Chapter IV.

Conclusions and recommendations are detailed in Chapter V. Chapter V covers the practical implications of the model action plan's operation and management application as well as recommendations for follow-on research. The model action plan is contained in Appendix A, and tables of cost data are included in Appendix B.

II. Background

Finding refrigerants with less ozone depletion potential and less impact on global warming than the current CFC refrigerants is a preeminent concern in the air-conditioning and refrigeration industry. DuPont, a major manufacturer of CFCs, "expects to spend $1 billion on the development of CFC alternatives by the end of the century" (50:41). The search for alternatives to CFCs includes research on hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs). The resurgence of a traditional refrigerant, ammonia, and a renewed emphasis on the absorption cycle are other avenues of research. This effort is in response to the legislation and regulations enacted due to global environmental concerns associated with release of CFCs into the atmosphere.

This chapter begins with a literature review covering directives, containment, refrigerant replacements, and alternative processes. The background also includes an overview of the model action plan, the underlying assumptions of the model, and a description of the context for which the model action plan should be used.

Directives

Current legislation, regulations, and policies for reducing the use and release of CFC refrigerants determine the constraints and boundaries of the model action plan. The review of legislation focuses on an international treaty, the Montreal Protocol, and Title VI of the 1990 Clean Air Act Amendments. Regulations affecting the Air Force include not only Air Force Regulations, but also those from the

Environmental Protection Agency and the Department of Defense. Relevant policies include those made by the Air Force and those adopted by the refrigeration and air-conditioning industry.

Legislation. Limitations on the use and release of CFCs were first highlighted in the international community by the Montreal Protocol, of which the United States is a signatory. The United States then enacted legislation to implement the accords of the Montreal Protocol.

Montreal Protocol. The industrialized nations of the world first gathered for the 1986 Vienna Convention to discuss the global issue of CFCs depleting the stratospheric ozone layer (28:51). The Montreal Protocol was signed by these same industrialized nations in Montreal, Canada in September 1987 (25:27). Further negotiations of the Montreal Protocol continued in June 1990 in London, England with an agreement to phase out CFCs by the year 2000. Based on a 1986 CFC production baseline, the phaseout calls for a 55 percent reduction by 1995 and 85 percent reduction by 1997 (34:21). The agreement also calls for a halt to HCFC production by July 1, 2020, if possible, but no later than January 1, 2040 (28:52).

Title VI, Clean Air Act Amendments (CAAA) of 1990. Title VI of the CAAA of 1990, titled Stratospheric Ozone Protection, begins by identifying the known ozone depleting chemicals. The refrigerants listed are CFC-11, CFC-12, CFC-114, CFC-115, and HCFCs. The CFC production phaseout schedule details a reduction to 85 percent of the 1986 production quantity in 1991 and termination of production by January 1, 2000. Figure 1 compares the CFC phaseout schedule under the CAAA to that under the Montreal Protocol. According to the CAAA, the release or venting of CFCs and HCFCs during maintenance or repair operations is prohibited effective July 1, 1992 (52:2650-2651,2662). Capturing and recycling used CFC and HCFC refrigerants is now mandatory.

The 1990 CAAA mandated that beginning in January 2020 no new HCFC equipment may be manufactured or sold in the U.S. In addition, the production and use of all HCFCs will be prohibited by January 2030 (28:52).

The Omnibus Budget Reconciliation Act of 1989 established a Federal excise tax on the sale or use of CFCs (28:53; 47:48). The tax rate increases yearly, as shown in Figure 2. The total tax is

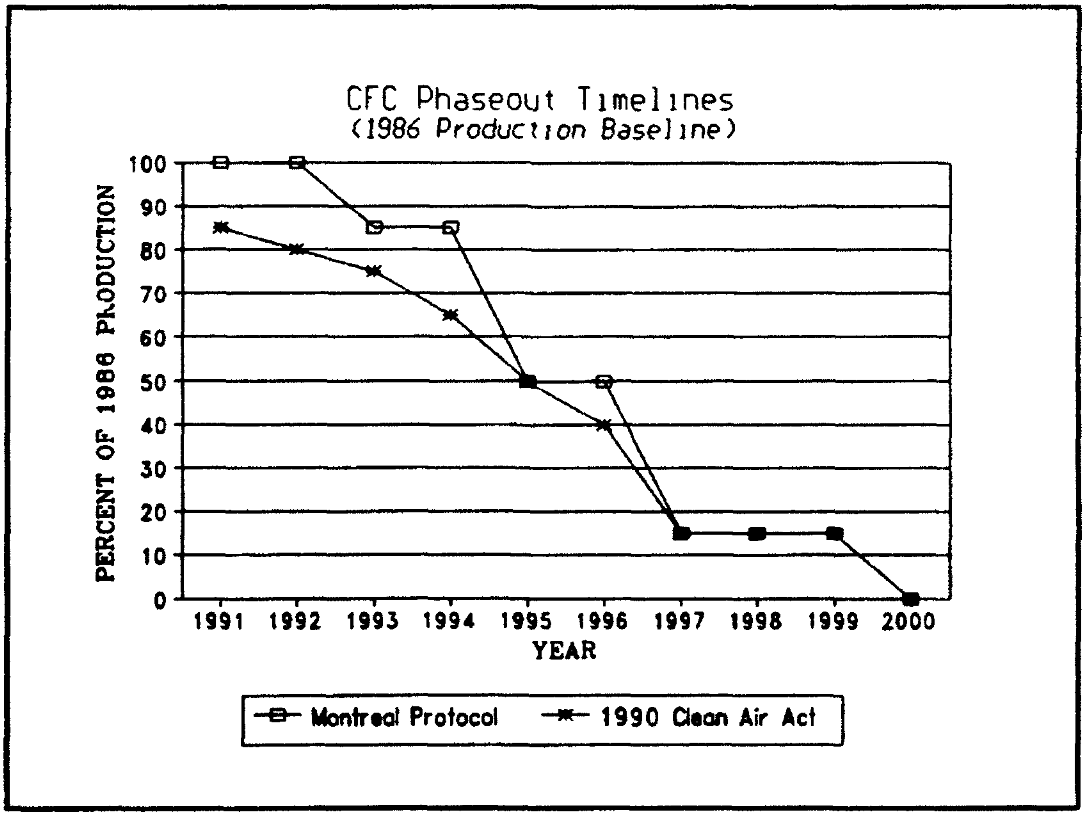

Figure 1. CFC Phaseout Timelines (21:38)

calculated as the tax rate multiplied by the amount of refrigerant purchased and by its ozone depletion potential (21:38). The tax serves as an economic incentive to discourage the continued use of CFCs and to stimulate the phaseout.

Regulations. The Air Force is developing its own regulations to control the use of CFCs, however it must also abide by similar regulations passed by the Department of Defense (DoD) and the Environmental Protection Agency (EPA).

EPA Regulations. The EPA is tasked in the 1990 CAAA to write regulations on monitoring and reporting, production and

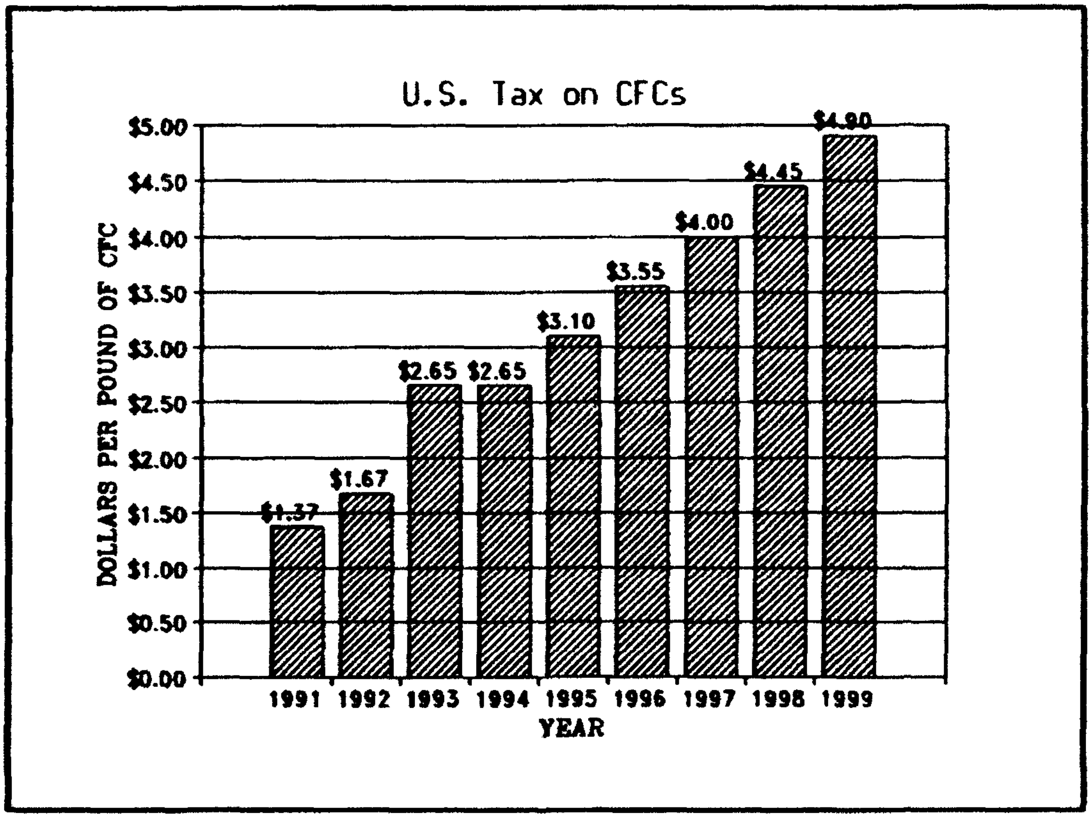

Figure 2. U.S. Tax Schedule for CFCs (21:38)

consumption, recycling and emission reduction, and labeling of CFCs (52:2653-2665). These regulations should be completed by the end of 1992. The EPA also has the responsibility to provide enforcement of legislation concerning CFCs (44:35).

DoD Regulations. The Department of Defense issued DoD Directive 6050.9, Chlorofluorocarbons (CFCs) and Halons dated February 13, 1989, to establish policy for management of CFCs and halons within the Department of Defense. (Halons are fire suppressants which also cause stratospheric ozone depletion.) This regulation establishes procedures that discourage and minimize CFC use, specifies conditions for CFC recycling and reuse, and requires monitoring the quantities of CFC being used (13:32).

Air Force Regulations. Draft AFR 19-15, Reduction in the Use of Chlorofluorocarbons (CFCs), Halons, and Other Substances that Deplete Stratospheric Ozone, was drafted on January 4, 1990 to implement DoD Directive 6050.9. The regulation sets restrictions on all ozone layer depleting substances (OLDS) including CFC refrigerants. The regulation divides OLDS into three usage categories. Category I, Mission Critical Use, applies to CFCs which "directly impact combat mission capabilities and are integral to, or used in direct support and/or protection of, mission assets" (19:6). Category II, Essential Use, applies to CFCs which "indirectly impact combat mission capabilities and play an auxiliary role in ensuring the operability of those assets" (19:6). Category III, Non-Essential Use, applies to CFCs which are "used in supporting routine system operations" (19:6). The majority of routine air-conditioning and refrigeration systems fall into Category III. Process cooling and refrigeration of perishables fall into Category II, while cooling of "...operational assets and mission critical personnel," including "...aircraft or missile crew compartments" are Category I (19:6).

The regulation will require Air Force bases to "institute plans to eliminate OLDS procurement and use" by October 1992 for applications in Category III and by October 1993 for Categories I and II (19:8). CFCs will be banned in new installations, and existing CFC use must be reduced to fifty percent of 1986 levels by October 1996, October 1997, and October 1998 for Categories III, II, and I respectively. By October 2000, no CFCs will be allowed in any application (19:8).

Policies. In addition to regulations, the Air Force developed policies to manage the CFC phasedown. Policies developed in the air-conditioning and refrigeration industry also influence the Air Force's management plan.

Refrigerant Manufacturing Policies. DuPont is the country's leading refrigerant supplier (51:4). A DuPont press release states that DuPont will not sell CFCs in the U.S. after December 31, 1996. The statement also stipulates that HCFC-22 will not be sold in new equipment after January 1, 2005 in developed countries (51:1).

Refrigeration Industry Standards. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) published Guideline 3-1990, Reducing Emission of Fully Halogenated CFC Refrigerants in Refrigeration and Air-Conditioning Equipment and Applications, to recommend standards to reduce and prevent CFC emissions throughout the life of equipment, from manufacture, to operation, through disposal (6:7).

ASHRAE's safety standards are being revised to update the safety classification of refrigerants and establish new safety requirements for equipment rooms (9:44). These changes are contained in ASHRAE Standard 15R, Safety Code For Mechanical Refrigeration, and ASHRAE Standard 34R, Number Designation and Safety Classification of Refrigerants.

Refrigerants will be classified according to their level of flammability and toxicity. The new safety standards include installation of refrigerant vapor and oxygen detectors, alarms, self-contained breathing apparatus, and ventilation fans in equipment rooms. The requirements differ based on the refrigerant's safety classification (9:45; 47:48).

Air Force Policies. Engineering Technical Letter (ETL) 91-7, Chlorofluorocarbon (CFC) Limitation in Heating, Ventilating, & Air Conditioning (HVAC) Systems, was signed on August 21, 1991. The purpose of ETL 91-7 is "to reduce the Air Force dependence on regulated CFCs as refrigerants in HVAC systems" (16:1). The policy letter details a three-part management strategy of containment, conversion, and change-out. It directs the Air Force to implement recycling and recovery of CFC refrigerants in existing equipment, conversion of existing equipment to approved non-CFC refrigerants, and replacement of aged equipment with environmentally sound equipment incorporating new technology.

> This criteria requires immediate implementation to reduce or eliminate Air Force dependence on CFCs for new HVAC equipment installations and to reduce and minimize Air Force CFC emissions in the routine operation, maintenance, and service of the existing inventory of installed HVAC systems. (16:1-3)

ETL 91-7 also furthers the recommendations of ASHRAE Standard 15R by prescribing high efficiency purging units and refrigerant recovery and recycling.

The Air Force, as of this writing, has also drafted a policy which would ban the purchase of CFCs effective October 1, 1993 (15:1). Realizing possible difficulties with meeting this deadline, the policy details "a two level appeal process to ensure mission continuity..." (15:1). The draft policy states that "previously recycled substances may be purchased for mission critical uses only if there is no alternative and only until a permanent fix can be implemented," and that "any function which cannot accomplish its mission using recycled or alternative material, may appeal for a waiver to continue purchasing new substances" (15:1).

Containment

The provision of the 1990 Clean Air Act Amendments that makes intentional release of CFCs and HCFCs illegal has forced the air-conditioning and refrigeration industry to change the standard practice of venting refrigerants when servicing equipment. The Alliance for Responsible CFC Policy estimates that by the year 2000 HCFCs and HFCs will only account for 39 percent of the CFC demand. "Conservation (including recycling & reuse) of CFCs will have to make up almost 30% of the shortfall" (47:48). Custodians of air-conditioning and refrigeration equipment which use CFCs must handle them in an environmentally responsible manner. That objective is met by implementing containment strategies consisting of efficient purging units, refrigerant recovery, recycling, reclamation, and disposal.

Purging. Air-conditioning and refrigeration systems designed to operate at low pressures often experience infiltration of air, water vapor, and other contaminants into the refrigerant cycle because the system pressure falls below atmospheric pressure. Air in the refrigerant can cause excessive temperatures, pressures, and corrosion thereby increasing energy consumption (31:28; 33:34). It is necessary to remove the contaminants from these systems using a purging unit. Some of the refrigerant is incidentally released during the purging process. This is especially true with low pressure chillers that use CFC-11.

Release of CFCs during purging can be minimized by improving purging procedures and by using more efficient purging units (44:36). Retrofitting existing low pressure chillers with efficient purging units can reduce CFC releases by 90 percent (16:2).

Recovery. Refrigerant recovery is "the process of removing and storing refrigerant from an air-conditioning system so the product can be serviced, maintained, or overhauled without the loss of its refrigerant charge to the atmosphere" (16:2). Containers used to hold recovered refrigerant must be appropriately labeled and be free of other refrigerants to enable subsequent reuse. Refrigerant recovery reduces release of CFCs to the atmosphere and permits recycling or reclamation (33:35).

Recycling. The first step in recycling is recovery of refrigerant. Recycling involves passing used refrigerant through filters and driers to remove contaminants such as water and lubricating oil. The recycled refrigerant is purged of air and is reintroduced into the machinery. Recycling a refrigerant is normally accomplished on-site (33:32).

The advantages of recycling are the on-site capability to service equipment and the reduction of new refrigerant purchased. The disadvantages are the costs of owning and operating the recycling equipment and the lack of refrigerant quality assurance. Air conditioner manufacturers provide warranties on their products only if the refrigerant meets specifications set forth by the Air-Conditioning and Refrigeration Institute (ARI). Standard ARI-700 specifies refrigerant purity, but there is no similar standard for recycled refrigerant. Inferior quality refrigerant may result in decreased efficiency, increased energy consumption, increased maintenance or repair, and shortened equipment life. In addition, special procedures must be taken to avoid contamination when the same equipment is used to recycle different refrigerants (33:32).

Reclamation. Reclamation differs from recycling in that the used refrigerant undergoes a distillation and purification process that removes contaminants more effectively than does the recycling process. When refrigerant is reclaimed, it must be sent to a laboratory which can certify that the reclaimed refrigerant meets the original specifications. Reclamation restores the refrigerant to its original like-new condition through distillation and chemical analysis.

Assurance of the continuing availability of high quality refrigerant is the main advantage of reclamation. The most significant disadvantage is the cost to purchase replacement refrigerant (33:32,34; 24:44).

Disposal. When a refrigerant is contaminated to the point of being unsuitable for either recycling or reclamation, it must be disposed. Refrigerant marked for disposal is first recovered then sent to an incinerator facility. Incineration destroys the refrigerant (24:44).

Implementing the appropriate containment strategies mentioned above effectively minimizes the release of CFCs to the atmosphere.

Refrigerant Replacements

Faced with the reality of a ban on CFCs, the air-conditioning and refrigeration industry is searching for replacement refrigerants that do not cause ozone depletion or that cause less harm than CFCs. "The chemical and equipment manufacturers have concluded that there will be no 'drop-in' CFC replacements" (47:48). Systems built to use CFC refrigerants will have to be retrofitted before they can be used with non-CFCs.

The search for replacement refrigerants has focused on hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs). HCFCs have less capacity for ozone depletion than CFCs, while HFCs have no ozone depletion potential. Both have less global warming potential than CFCs.

The ozone depletion potential, ODP, is the measure of a chemical's capacity to destroy stratospheric ozone. The ODP gauges relative depletion potential compared to CFC-11, which is assigned an ODP of 1. Global warming potential, GWP, gauges the capacity of a chemical to contribute to global warming relative to carbon dioxide. The GWP of carbon dioxide is assigned the value of 1. ODP values and GWP values for selected refrigerants are shown in Figure 3 and Figure 4, respectively.

Hydrochlorofluorocarbons (HCFCs). The hydrogen bond in hydrochlorofluorocarbon molecules makes them more susceptible to break down by ultra-violet radiation than CFCs. HCFCs do not persist in the

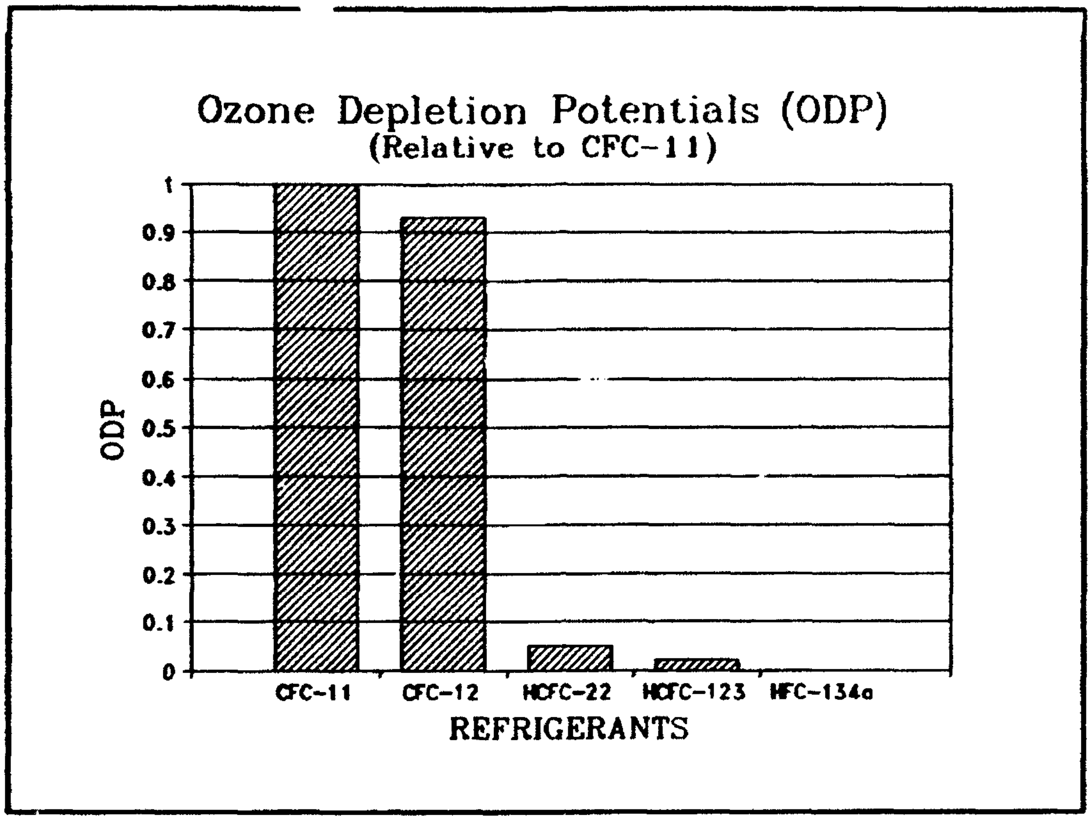

Figure 3. Ozone Depletion Potential of Selected Refrigerants (21:39)

atmosphere as long as CFCs, have a lower impact on global warming, and have less potential to deplete ozone because they contain fewer chlorine atoms than CFCs.

HCFCs are regulated under the 1990 Clean Air Act Amendments. Like CFCs, HCFCs cannot legally be vented to the atmosphere. The freeze on HCFC production is currently legislated for 2015, with a complete phaseout no later than 2030 (21:38). HCFC refrigerants with potential as CFC substitutes include HCFC-22, HCFC-123, and HCFC-124 (50:42).

HCFC-22. HCFC-22 is already used in many air-conditioning and refrigeration applications and is considered a replacement for CFC-12 in new systems. The ODP and GWP values for HCFC-22, 0.05 and 510 respectively, are significantly lower than those for CFC-12, 0.93 and

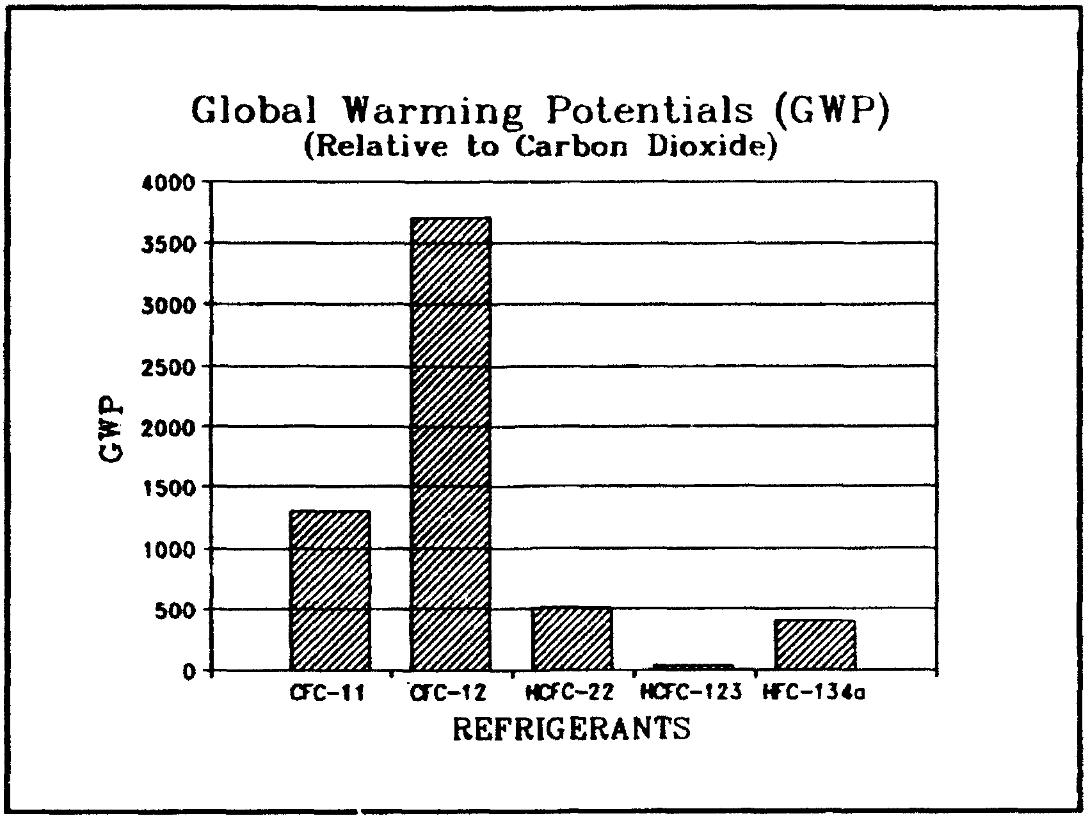

Figure 4. Global Warming Potential of Selected Refrigerants (21:39)

3,700 respectively (21:39). Residential applications of HCFC-22 are very common in window air-conditioning units and residential heat pumps (10:41). HCFC-22 is used commercially in refrigeration, large unitary air-conditioning units, and large chillers (27:45).

HCFC-22 has been successfully tested as a substitute for CFC-12 and CFC-502 in retrofitted supermarket refrigeration systems. There is some loss of efficiency in the process, but HCFC-22 "is the only alternative for supermarkets for the foreseeable future" (1:26). There is an economic incentive for converting existing CFC-12 systems to HCFC-22. In 1990, the cost of HCFC-22 was $1.72 per pound compared to $3.53 per pound for CFC-12 (1:26). HCFCs will be even more economical as the tax on CFCs increases.

The drawbacks to HCFC-22 are the high operating temperatures and pressures involved. These characteristics create the need for special compressor requirements and cause compatibility problems with certain materials in existing equipment. These problems can be overcome but not without increasing the cost of conversion.

CFC-12 is the standard refrigerant used in automobile air conditioners. The high discharge temperatures and material compatibility problems of HCFC-22 make conversion to HCFC-22 in automobile air-conditioning systems infeasible (48:24,26).

HCFC-123. HCFC-123 is a workable refrigerant to replace CFC-11. HCFC-123 has the potential to fill a large segment of the refrigeration market since CFC-11 is used in eighty percent of centrifugal chillers (48:26). Compared to the ODP of CFC-11 at 1.0, the ODP of HCFC-123 is very small, 0.02. HCFC-123 has similar operating pressures to CFC-11 systems. "Of the alternatives available, only HCFC-123 can be used in existing equipment designed for CFC-11 due to its pressure rating" (11:38-39).

The main drawback in converting from CFC-11 to HCFC-123 is loss of efficiency and cooling capacity. A 15 percent drop in efficiency and 10 to 15 percent loss of cooling capacity can be expected when switching to HCFC-123 (11:39-40). The decrease in performance can be partially offset by making modifications to the machinery during retrofitting. Installing impellers with larger diameters and passages and changing drive gears to increase compressor speed results in increased refrigerant flow and improved performance. Improving the heat exchange surfaces and adding economizers can also boost performance (22:38; 27:45).

HCFC-123 is a strong solvent and is not compatible with the polymeric materials used in CFC-11 equipment for parts such as gaskets, seals, and motor winding insulation. New materials will be needed in HCFC-123 retrofitted equipment and preliminary studies suggest the problem can be overcome (48:26). Chillers retrofitted for HCFC-123 will require new motors, gaskets, bushings, and seals (11:39).

HCFC-124. HCFC-124 is a likely candidate to replace CFC-114 in marine refrigeration, chillers, and CFC blends. HCFC-124 has a very low ozone depletion potential of 0.02, versus 0.71 for CFC-114, and a low global warming potential of about 130, versus 6,400 for CFC-114 (41:40; 2:6). HCFC-124 is used in blends with HCFC-22 and HFC-152a to achieve higher efficiencies. One problem with HCFC-124 is its requirement for an unconventional lubricant to achieve desired mixing properties. HCFC-124 is also undergoing toxicity testing (41:40-41; 48:24).

Conversion to HCFC refrigerants is feasible, but only as a temporary solution, because HCFCs still contribute to ozone depletion and to global warming. Under current legislative and industry guidelines, production of HCFCs will cease by the year 2020, or possibly earlier (51:1). Restrictions on the use of HCFCs could have "a devastating effect on the industry" if suitable alternatives are not found (48:24).

Hydrofluorocarbons (HFCs). Hydrofluorocarbons contain no chlorine atoms and thus have no ozone depletion potential (32:413). HFC-134a and HFC-152a are two HFCs with good potential for replacing CFCs.

HFC-134a. HFC-134a is a leading candidate for replacing CFC-12 (36:1). HFC-134a is a candidate for use in medium pressure chillers which use CFC-12 and CFC-500. The operating pressure of HFC-134a is similar to that of CFC-12. There is decreased compressor performance with HFC-134a, but heat transfer properties are increased and HFC-134a can achieve better performance than CFC-12 in some applications (11:38, 40-41).

HFC-134a is more stable than CFC-12, but HFC-134a is incompatible with the mineral oils that are used for lubrication in CFC-12 systems (11:41). Compatibility tests of HFC-134a with lubricants provide data about heat transfer properties and system efficiencies (49:37). HFC-134a retrofit applications work with ester-based lubricants. For new HFC-134a chillers, only polyalkylene glycol-based (PAG) lubricants can be used (39:6). Retrofitting can be successful using new lubricants and modifications to increase centrifugal compressor speeds.

Though "the automotive industry has committed to R-134a as the substitute for R-12," there remain problems related to "lubricant selection and compatibility with elastomers" (48:26). HFC-134a is undergoing toxicity evaluation (50:42).

<u>HFC-152a</u>. R-152a is a candidate replacement in centrifugal chillers that use CFC-12 because of its excellent thermodynamic properties. Its major drawback is its flammability (48:26). Blending HFC-152a with other refrigerants can overcome this drawback (7:34). Further research of compatibility with lubricants and elastomeric and polymeric materials can provide data needed to evaluate the suitability of HFC-152a as a refrigerant (48:26).

<u>Ammonia</u>. Ammonia has been used as a refrigerant since the 1850s and "is still the refrigerant of choice in industrial refrigeration" (35:43). Ammonia poses no threat to the ozone and does not contribute

to global warming. As far as its "thermodynamic and thermophysical properties, ammonia is almost the nearly perfect refrigerant" (12:28).

The advantages that ammonia offer as a refrigerant are many. It is an efficient heat transfer fluid with four to five times the heat capacity and conductivity of CFC-12 and HCFC-22 (12:28). This allows smaller heat exchangers than those for CFC systems. The molecular weight of ammonia is considerably lower than for CFCs, resulting in less friction losses, less energy required to circulate the fluid, (12:30) and a savings in piping costs (37:34). Ammonia has a high tolerance for water (37:34) and is highly compatible with conventional lubricants (12:30). Ammonia is in abundant supply and inexpensive, costing around 25 cents per pound in 1990 (12:31).

The use of ammonia as a refrigerant has some disadvantages. The low molecular weight requires that multi-staging compressors be used to achieve the necessary working temperatures. This causes the compressors to be very expensive. Ammonia systems have very high discharge temperatures. This leads to expensive refrigerant cooling systems and reduced efficiencies. Recent developments in high efficiency screw compressors have reduced the effect of high discharge temperatures and made ammonia systems more practical (12:30-31).

The biggest problem with ammonia is its health hazard. "Ammonia is a toxic chemical, it is dangerous in excessively high concentrations, and it is classified as an extremely hazardous chemical by the Environmental Protection Agency" (12:32). Ammonia is also classified as moderately flammable. Careful design and appropriate health precautions are needed to make ammonia systems safe (12:32). Ammonia is a workable alternative to CFCs in air-conditioning, refrigeration, thermal storage, and chilled water systems if special precautions are taken (35:44). The health risks associated with ammonia make it less desirable than other available refrigerants in most applications.

Alternative Processes

The use of existing air-conditioning and refrigeration processes that do not use CFCs may expand to meet the need for non-CFC alternatives. One process that must be considered is the absorption cycle.

The absorption cycle offers an alternative to the vapor compression cycle, which generally uses CFCs. The vapor compression cycle uses a compressor, and its energy input is "entirely in the form of work" (26:68). In contrast, the energy input of an absorption cycle are a combustion, solar or electrical resistance heat source, and a small fluid circulating pump. Absorption systems can operate using steam or natural gas combustion, while vapor compression systems operate using electricity.

Another difference between absorption and vapor compression cycles is the working fluids used. The working fluid in an absorption cycle consists of the combination of an absorbent and a refrigerant. Two common refrigerant/absorbent fluid combinations are ammonia/water and water/lithium bromide. Water is the absorbent in the former and the refrigerant in the latter (26:69). These working fluids have zero ozone depletion and global warming potentials (21:39).

Absorption cycles are fuel efficient since they require little work input and can operate on waste heat. "Using absorption cycles to recover waste heat can contribute to overall energy efficiency"

(26:70,73). Since they do not use mechanical compressors, absorption systems produce little noise (30:1060). Practical applications of absorption systems include refrigeration and heat pumps (26:70).

Conclusion of the Literature Review

The Air Force must develop and implement a management plan to deal with the phasedown and ultimate ban of CFCs in air-conditioning and refrigeration systems. The management plan must integrate elements of containment, refrigerant replacement, and alternative processes to comply with CFC directives.

The Air Force's philosophy is to stay ahead of government legislation. An Air Force wide ban on CFC purchases starting October 1993 is sooner than the phaseout schedule mandated in the 1990 Clean Air Act Amendments. The date also falls before the earliest projected CFC production cessation.

Refrigerant recovery and recycling or reclamation are now mandatory since the CAAA prohibits the intentional release of CFCs and HCFCs into the atmosphere. Recycling and reclamation are essential to ensure the continuing supply of quality refrigerants during the phaseout process. Reducing unintentional releases of CFCs and HCFCs can be accomplished through recovery, high efficiency purging units, and proper disposal.

Although development of new technologies and refrigerants to replace CFCs is continuing, practical replacements for CFC-11 and CFC-12 have already been found. There are no drop-in substitutes available, but conversion of existing systems is possible. Some existing systems that use CFCs may be retrofitted to use HCFCs or HFCs after making a few modifications. More specifically, systems with reciprocating, screw, or rotary compressors may be converted to run with HFC-134a as the refrigerant. Systems with a centrifugal compressor using CFC-11 can be converted to operate with HCFC-123. The drawback is that systems that are converted to a different refrigerant become less efficient and lose cooling capacity. Efficiency loss and capacity reduction can be partially restored in systems with centrifugal compressors by re-engineering the compressor to boost performance. Retrofitting may be a good alternative only if capacity and efficiency reductions are acceptable.

In situations where retrofitting is not practical, replacement of the existing system with a completely new non-CFC system becomes necessary. Systems currently using CFC-11 may be replaced with HCFC-123 systems. Similarly, systems using CFC-12 may be replaced with HFC-134a systems. Other alternatives are absorption systems and HCFC-22 systems with reciprocating compressors or screw compressors. Air conditioners using HFC-134a will be replacing the CFC-12 currently used in automobile systems.

HCFC-124 is a suitable replacement for CFC-114 in marine chillers. However, this application is not typical on an Air Force installation and does not warrant further discussion. HFC-152a is highly flammable and is not expected to come into wide use. Ammonia is a proven refrigerant but is gaining limited popularity as a replacement for CFCs due to health hazards. Ammonia systems are not seen as a suitable alternative in typical Air Force applications at the present.

HCFC-123 and HCFC-22 are used in a multitude of new applications and while they offer near term solutions, their long-term benefits are limited. With a ban on HCFCs in 2020 or earlier, new refrigerants must be developed to replace them. Research and development of new refrigerants is an on-going effort. In summary, cost-effective non-CFC solutions depend on product availability, economics, and policies. Managers of air-conditioning and refrigeration equipment must remain knowledgeable of the latest developments in technology and legislation.

Overview of the Model Action Plan

In order to be effective, the model action plan (MAP) must provide a logical sequence of steps to take the manager from the problem of CFC use and reduction to an economical solution to that problem. The population of the model action plan consists of air-conditioning and refrigeration equipment commonly found on an Air Force base. The common characteristic of the equipment in the population is that CFCs serve as the refrigerant. The plan begins by identifying the boundaries through a literature review of the directives, containment methods, refrigerant replacements, and alternative processes. The plan then proceeds with a life cycle cost comparison of the feasible alternatives to select the most cost effective solution.

Scope of the Model Action Plan. A planning document must have constraints to guide the boundaries of that plan. Directives, refrigerant substitutes, and alternative processes place limits on the MAP.

Current legislation, regulations, and policies form the timetable for the MAP. The MAP follows the requirements of the Clean Air Act Amendments of 1990 and AFR 19-15 draft to eliminate use of CFCs in all applications by October 2000. The MAP assumes the draft Air Force policy to end CFC purchases in October 1993 is adopted. Therefore, the MAP will address the recovery and reuse of current CFC refrigerants during maintenance or replacement of refrigeration equipment, mandatory as of 1 July 1992, through the year 2000. The MAP also assumes that HCFCs will be available for purchase through 2020.

Refrigeration and air-conditioning systems using R-11 and R-12 are the target of the MAP. The CFC blend R-500, which is composed of 74 percent CFC-12 and 26 percent HFC-152a, is treated in the same category as CFC-12.

Alternative solutions to reduce the use and release of CFC identified through the literature review include maintaining the existing equipment through CFC recovery and reuse, replacing the CFC refrigerant with a non-CFC refrigerant in a retrofit procedure, or replacing the equipment with new non-CFC equipment.

Replacing a CFC refrigerant requires purging the existing system of all CFC refrigerant, replacing the gaskets, seals, and motor windings that are not compatible with the new refrigerant, then introducing the substitute refrigerant. The feasible substitute refrigerants for CFC-11 and CFC-12 in many applications are HCFC-123 and HFC-134a, respectively. Other HCFCs and HFCs are still in the developmental stages and are not considered viable solutions for the MAP.

The final non-CFC strategy is to replace the existing equipment with a new system. HCFC-123, HCFC-22, HFC-134a, or ammonia are alternatives when considering vapor compression cycle air-conditioning and refrigeration systems. An alternative to the vapor compression cycle is the absorption cycle using ammonia/water solutions in small systems or water/lithium bromide solutions in large systems.

Cost Analysis. The MAP will include information and recommendations for decision-making. After determining the available alternatives for each category of CFC equipment, a life cycle cost analysis will identify the recommended alternative based on the least life cycle cost. Those factors included in the cost analysis are the initial, operation and maintenance, overhaul, energy, and salvage costs. Since the product of this process is a model, a manager implementing the conversion from CFC refrigerants should consider the advantages and disadvantages included in this document as well as the cost analysis.

Underlying Assumptions of the Model

The MAP does not cover every possible management situation dealing with CFCs in refrigeration and air-conditioning applications. Areas of assumptions relate to policies, technology, and cost data.

Creation of the boundaries for the MAP are based on current policies. Policies for CFCs as they affect the environment and industry are constantly changing due to world opinion, senior leadership decisions, and product manufacturing policies.

The alternatives identified for CFC equipment replacement or retrofit are based on the successful implementation of current technologies. Research into new refrigerants and products is continuing for many applications. Only approved products can suffice as feasible alternatives.

The cost data used to evaluate selected alternatives will be for a common application. A typical application for air-conditioning is an office building. Due to the wide use of refrigeration and air-conditioning systems throughout the Air Force, a model must identify the most common and note differences as exceptions. To equate costs of different alternatives, the equipment application and operation time will remain constant. The cost analysis will compare systems for use in an office building. The cost data will be reflected in the usage, size, and maintenance requirement based on office design requirements. The standardization of operating times will insure comparable energy usage and scheduled overhaul costs.

Context for Model Action Plan Use

The model is designed to assist and guide managers of CFC refrigeration and air-conditioning equipment to a rational conversion to a system containing no CFCs. The MAP contains a listing of practical alternatives and recommended actions for a general case. The MAP also conveys the methodology necessary to perform an evaluation in a specific situation. The manager must first inventory all CFC containing equipment. Then, using the MAP, determine the most economical alternative for replacement of the CFC or equipment identified. Considering all the advantages and disadvantages of the alternative replacement proposed in the MAP, the manager then makes a decision on the course of action.

III. Methodology

This thesis uses existing data to develop a quantitative model to recommend alternatives to CFC refrigerants in air-conditioning and refrigeration systems. The end product is a model based on a descriptive study of current refrigerant technologies in the air-conditioning and refrigeration industry. Understanding the model's limitations and sensitivity to input parameters contribute to the validity of the model. How well the model satisfies the research objectives is a measure of its practicality.

Model Action Plan Development

The methodology for developing the model action plan combines collecting information to generate alternatives, evaluating alternatives, and presenting findings.

Background Research. The principle method used for collecting information to develop the model action plan was a literature review. The literature reviewed included current technical journals; proceedings from professional association conferences; U.S. Air Force regulations, engineering technical letters, and draft policies; reports from private firms contracted by the United Nations Industrial Development Organization and U.S. federal and state agencies; and publications from corporations in the air-conditioning and refrigeration industry. Since research and development of new refrigerants is on-going and there is a time delay in literature publication, telephone and personal interviews with people from industry were conducted to update, clarify, and supplement the information obtained by literature review.

The literature review covered four subject areas: directives, containment methods, refrigerant replacements, and alternative processes. These subjects relate directly to the investigative questions posed in the introduction. Researching directives identified the specific refrigerants targeted for phaseout and the air-conditioning and refrigeration systems which the model action plan should include. Studying containment revealed methods of CFC recovery and reuse instrumental during the transition period leading to ultimate CFC phaseout. Researching refrigerant replacement identified new and existing non-CFC refrigerants. The non-CFC refrigerants may be used in new equipment and, in some cases, used to retrofit existing equipment. Lastly, studying alternative processes showed that absorption systems are a viable alternative to CFC vapor compression systems in some applications.

Evaluating the Alternatives. The literature review generated a list of feasible non-CFC alternatives. The model action plan evaluates the alternatives primarily with an economic analysis of life cycle costs. There were a number of decision models considered for evaluating alternatives before deciding on an economic analysis.

Selection of an appropriate decision theory depends on the characteristics and environment of the decision and the degree of uncertainty and risk involved (42:156). This thesis deals with the problem of reducing the use of CFC refrigerants. Having to decide which available alternatives to choose is driven by legislation and policy and not necessarily by a profit motive. Decision models based on profit or value rely on probabilities, risk, and future states of nature (42:155). These models, which may use expected monetary values, marginal analysis, utility theory, and Markov analysis, were considered not appropriate for choosing among non-CFC alternatives. Network models, such as program evaluation and review technique and critical path method, are activity oriented and not applicable either.

Linear or goal programming could be applied in a decision model to choose among feasible alternatives. The necessary criteria to prepare linear programming problems are an objective to minimize or maximize a value, constraints, alternative courses of action, and the expression of these in terms of linear equations or inequalities (42:354-355). A linear programming model could be formulated to reduce the use and release of CFCs at an Air Force base with an objective function that minimizes the ozone depletion potential of the alternative refrigerants.

A model based solely on eliminating CFCs by minimizing ozone depletion fails to account for costs of conversion to new systems. Cost is a key component in managerial decision making and would have to be included. Due to limited budgets, costs are an overriding factor when compared to ozone depletion potential as a decision criterion. Linear programming models are not as effective as economic analyses in evaluating costs of alternative systems.

The decision to use an economic analysis of life cycle costs in the MAP is a natural consequence of the problem statement to economically reduce the use and release of CFCs. Eliminating CFC refrigerant systems within Air Force facilities in a timely manner is solely based on the availability of funds.

The life cycle cost method is also dictated in Air Force Regulation (AFR) 88-15. AFR 88-15 states that mechanical equipment projects will be accomplished "to ensure an adequate level of building environmental condition at the least life cycle cost" (17:15-98). The cost factors in the life cycle cost method used in the model action plan include initial costs, energy costs, operation and maintenance costs, overhaul costs, and salvage costs.

Evaluating the Recommendation. The model action plan returns a recommendation based on an economic analysis. A refrigeration and air-conditioning systems manager must evaluate the recommendation based on factors that are application specific. There are factors other than economics that influence the selection of alternatives.

One factor involves cooling capacity. A retrofit method may be economically attractive but it is accompanied by a loss of cooling capacity. If the resulting decreased cooling capacity does not meet the minimum cooling load required, that alternative cannot be a suitable option.

Another factor that may influence selection of alternatives is policy. For example, the alternative with the least life cycle cost may be recovery and reuse of the CFC refrigerant. That option is useful only to the point when, due to regulation or policy, the use of the refrigerant is banned.

Model Action Plan Framework. The model action plan contains feasible alternatives and outlines the evaluation factors for choosing the best alternative. The model begins with categories of CFC equipment impacted and logically flows to a list of viable alternatives. The alternatives are evaluated through life cycle cost analyses to arrive at the best economic alternative. The model illustrates a general case and details the assumptions made. The reader may then adapt the model to specific applications.

Validation

The aim of the model action plan is an aid in decision making. The plan achieves this aim by presenting a list of feasible options and recommending the best one based on life cycle costs. The plan is modeled after a typical air-conditioning application and is intended for broad implementation. Knowing the model action plan's limitations and sensitivity to input parameters weighs heavily on its successful implementation.

Limitations. The ability to apply the model action plan to a broad spectrum of air-conditioning and refrigeration applications is valuable. A drawback to having a broad scope is the limited amount of detail included. For example, the model action plan assumes a standard air-conditioning or refrigeration system and does not attempt to differentiate between system types. The level of detail included in the plan is sufficient to enable comparisons in comparable operating environments only.

The model action plan demonstrates a methodical procedure to economically select non-CFC air-conditioning and refrigeration alternatives. However, the recommendations derived by the model are generalizations. Specific situations may exist in which the recommendations stemming from the model action plan may not be optimal.

The model action plan makes generalizations about operating conditions and maintenance procedures. The model action plan does not account for possible changes in policies or technological developments. To be used effectively at the operational level, the methodology of the model action plan should be followed with the actual conditions and values for the specific application. Understanding the underlying assumptions of the model action plan is crucial to its effectiveness as a decision-making aid.

Sensitivity to Input Parameters. The economic analysis is based on assumptions made about the operating environment of the air-conditioning or refrigeration systems. The recommendations resulting from the economic analysis are therefore valid only in comparable situations. The recommendations are not meant to be rules applicable to all scenarios. The more the actual operating conditions and maintenance procedures vary from those used in the action plan, the greater the likelihood of the recommendations being inaccurate. The model includes a detailed description of the methodology to enable the user to make the necessary changes in input parameters to suit the specific application.

There are a number of input parameters that affect the outcome of the economic analysis including costs, service life, and location. Equipment and energy costs can fluctuate widely with location and over time. Estimates of values for an equipment's useful life or efficiency are imprecise because they vary greatly with maintenance practices and operating conditions. Changes to equipment costs and service life can affect a change in the solution of the economic analysis.

The service history and maintainability of existing equipment may affect performance. Equipment alternatives and product availability vary according to manufacturers. To illustrate, some equipment cannot be retrofitted with a replacement refrigerant simply because the manufacturer does not invest an effort into equipment conversion.

Validity. The ability of the model action plan to be generalized for different applications and locations is one measure of external validity. The extent to which consistent recommendations are reached further contributes to validity (20:180,185). The model action plan is a functional instrument which can help managers make informed decisions.

Meeting Research Objectives

The research methodology satisfies the initial research objectives stated in the introduction. The literature review investigated the legislative, regulatory, and policy requirements of the model action plan. The literature review also examined containment methods which are imperative to any effort aimed at reducing CFC releases. The literature review identified non-CFC refrigerants and revealed non-CFC processes that were included in the model action plan. An economic analysis based on life cycle costs served to evaluate the non-CFC alternatives. The model action plan efficiently combines all research objectives in a concise plan with broad application.

IV. Findings and Analysis

The MAP is designed to guide a manager to an acceptable decision for the replacement of CFC containing air-conditioning and refrigeration equipment. The plan first identifies alternative systems to the existing CFC refrigerant equipment. The plan then makes a generic comparison of the life cycle costs of those alternatives. Finally, the plan recommends a decision based on the economic analysis.

Alternatives for Existing CFC Refrigerant Systems

The literature review identified the alternatives for existing systems in the Air Force which typically use CFCs as refrigerants. These include package units, reciprocating chillers, and centrifugal chillers. An alternative in all cases is to continue to maintain the existing systems. Maintaining the existing systems is only a viable alternative until the year 2000 when the Air Force is forced by legislation to eliminate all CFC containing equipment.

Package Units. The practical alternatives for CFC package units include maintaining the existing system or purchasing a new package system. While retrofitting is possible, the associated loss of cooling capacity and energy efficiency make it an unattractive alternative. Retrofitting may be practical only if the existing system were oversized, could be used in a different application, or could be supplemented with another system. Only one major U.S. air conditioner manufacturer supports a program to retrofit their package systems. Therefore, retrofitting a package unit with a non-CFC refrigerant is not a feasible alternative in the MAP.

Reciprocating Chillers. Alternatives for reciprocating chillers include maintaining the existing systems, installing new reciprocating chillers, installing new absorption systems, or installing new screw chillers. Absorption systems use natural gas or steam instead of electricity to operate the systems. The MAP compares this alternative assuming natural gas or steam is available. This may not be a feasible alternative at every base or location. The manufactured sizes of screw chillers range from 140 to 650 tons (40). Therefore, screw chillers are not an alternative for all sizes of reciprocating chillers.

Retrofitting existing reciprocating systems with new non-CFC refrigerants results in significant decreases in efficiency and cooling capacity because the cooling capacity of reciprocating compressors is based directly on the compression and expansion of the refrigerant. This loss of capacity is unacceptable in most situations unless the system is significantly oversized. Retrofitting is not considered a practical alternative in the MAP.

Centrifugal Chillers. Alternatives for centrifugal chillers include maintaining existing systems, retrofitting existing systems, installing new centrifugal chillers, installing new absorption systems, and installing new screw chillers. Since the size and speed of the impellers in a centrifugal chiller can be modified, the loss of cooling capacity is acceptable with a retrofit of non-CFC refrigerants. Since centrifugal chillers use both CFC-11 and CFC-12, the retrofit replacements are HCFC-123 and HFC-134a, respectively. The absorption system alternative in this case is based on the availability of natural gas, steam, or other energy for a heat source.

Life Cycle Cost Analysis

A total life cycle cost (TLCC) analysis is the decision model used to determine the most cost-effective systems in the MAP. To equate the costs of each alternative, the model cost estimates are based on a theoretical system located at Wright-Patterson AFB, OH. The cost estimates are based on actual costs incurred at Wright-Patterson AFB or the local Dayton area or converted costs using an area cost factor for Dayton. The costs included in a TLCC analysis are identified in the following equation (46:14):

$$TLCC = I - S + M + R + E$$

where

I = investment costs
S = salvage value
M = non-fuel operation and maintenance costs
R = replacement costs
E = energy costs

The model assumes that the replacement costs and salvage value are zero. Since the evaluation looks at one equipment life cycle, no replacement cost is used. When the decision is made to replace an existing system because it uses a CFC refrigerant or it is at the end of its useful service life, it has essentially zero immediate value to the Air Force. In general Air Force practice, the replaced equipment is not sold for salvage but becomes the property of the contractor installing the new system.

Investment Costs. The investment or initial costs of a system include the costs associated with changing or replacing a system. If the alternative is to change or retrofit existing equipment with a non-CFC refrigerant, the estimate for initial cost includes replacing the

CFC refrigerant, the gaskets and seals, and the compressor motor. Retrofit estimates are based on industry standards (40). If replacing the existing system is the alternative, the cost estimates include removing the existing system and installing a new non-CFC refrigerant system in accordance with current standards (38:219-237). The 1992 Means Mechanical Cost Data publication provides cost estimates for new systems (38:219-237). The "City Cost Index" section of the publication provides the mechanical construction cost index of 93.9 percent to convert the estimate for the Dayton area (38:421).

Operation and Maintenance Costs. Equipment operation and maintenance costs are broken down into two types, annual recurring and non-annual recurring. Annual recurring costs are estimated based on periodic maintenance throughout the year to keep the equipment running (40). Non-annual recurring costs are estimated based on a manufacturer's scheduled overhaul or restoration efforts, normally around the five to ten year points, depending on the usage, which prolong the useful life of the equipment (40). This model assumes that repair costs are zero when the equipment manufacturer's recommended preventative maintenance is followed.

Energy Costs. Many factors influence the energy requirements for a cooling system. Some of these factors are the equipment capacity and efficiency, loading, and maintenance. The energy usage is also dependent on the type of building construction. This makes it difficult to accurately predict or calculate the long term energy costs. To obtain a relative cost to compare alternatives, the model estimates cooling energy using the following equation for cooling energy as defined in the 1989 ASHRAE Fundamentals Handbook (5:28.1-8).

$$E_c = 24 * BLC * CDD * (1 + DLF) / COP$$

where

E_c = cooling energy (Btu/yr)
BLC = building loss coefficient (Btu/h·°F)
CDD = cooling degree days (°F·days/yr)
DLF = duct loss factor
COP = average coefficient of performance

This equation assumes that the cooling equipment crankcase heater and the ventilative cooling are similar in all alternatives.

The building loss coefficient is a measure of the amount of heat gain or cooling loss of the building through the building materials and infiltration. Since the model is not based on an actual building, the building loss coefficient is calculated from an equation relating BLC with heat gain, indoor cooling temperature, and cooling balance temperature (5:28.7). The equation is:

$$BLC = q / (t_i - t_b)$$

where

BLC = building loss coefficient (Btu/h·°F)
q = total heat gain (Btu/h)
t_i = indoor cooling temperature (°F)
t_b = cooling balance temperature (°F)

The cooling balance temperature is the outdoor temperature at which the building interior remains at the design temperature without requiring air-conditioning. For the purposes of this model, the total heat gain is equal to the rated capacity of the system. This assumes equipment sized perfectly for the load. The model assumes a typical balance temperature of 55°F and a summer cooling design temperature of 75°F.

This model uses cooling degree-days as an indication of cooling energy quantity. A value of 1036 °F·days, the actual annual cooling degree-days at Wright-Patterson AFB, is used consistently in the model

(18:5-14). The cooling degree-days method is simple and suitable for the purposes of this model. Other more complicated methods of calculating cooling energy are available and offer increased accuracy when estimating cooling energy in specific applications.

The duct loss factor is the amount of cooling lost from the cooling equipment to the conditioned space through the air supply ducts. This model assumes a five percent loss of cooling capacity which increases the amount of cooling and energy.

The coefficient of performance (COP) is a measure of a system's efficiency and is a ratio of a system's cooling output to its energy input. Table 2 identifies an estimated COP for each type of system used in the model. More efficient units will have higher COPs. The COP

TABLE 2

COEFFICIENT OF PERFORMANCE ESTIMATES

Equipment Item	COP
Package Systems	2.55
Reciprocating Chillers	4.00
Centrifugal Chillers	5.70
Screw Chillers	4.55
Absorption Systems	1.00

(21:40)

varies with equipment loading, so an average COP must be used to estimate cooling energy. In this model, there is no appreciable difference between the estimated COPs given in Table 2 and the calculated values of average COPs.

When the cooling energy, in British thermal units (Btu), is converted for each system using the conversion factors of 3412 Btu per kilowatt·hour (kWh) of electricity and 100,000 Btu per hundred cubic feet (CCF) of natural gas (8). The energy is then converted to a cost based on the current utility rates at Wright-Patterson AFB. The utility rates for Wright-Patterson AFB are given in Table 3. When using the MAP, the actual utility costs for each particular base must be used.

TABLE 3

ENERGY COSTS AT WRIGHT-PATTERSON AFB

Utility	Cost
Electricity	$0.042/kWh
Natural Gas	$0.395/CCF
Steam	$7.38/MBtu

where kWh = Kilowatt-hour
CCF = One-hundred cubic feet
MBtu = Million Btu

(43)

Once all of the relevant costs are accumulated, the model calculates and compares equivalent uniform annual costs for each alternative. The expected useful lives of the alternatives are different (Table 4). The costs of the alternatives must be compared using a common time reference in order to have equivalent costs (23:141). The equivalent uniform annual cost method is used to compare alternatives with different service lives on an equivalent basis. To

TABLE 4

EQUIPMENT SERVICE LIFE ESTIMATES

Equipment Item	Median Years
Package Systems	15
Reciprocating Chillers	20
Centrifugal Chillers	23
Screw Chillers	23
Absorption Systems	23
	(4:33.3)

obtain annual equivalent amounts from future values, the future values are first converted to present equivalent amounts using the equation (23:56):

$$PE = F / (1 + i)^t$$

where
PE = present equivalent amount
F = future amount
i = discount rate (percent)
t = number of years from the present

Annual equivalent amounts are then calculated using the equation (23:56):

$$AE = PE * \{ i*(1 + i)^n / [(1 + i)^n - 1] \}$$

where
AE = annual equivalent amount
PE = present equivalent amount
i = discount rate (percent)
n = number of years in the life cycle

To get an equivalent uniform annual cost for the life cycle costs of each alternative, the MAP uses the Building Life Cycle Cost computer program, version 3.1 (14). The TLCC analysis performed in the MAP uses the Federal project analysis in the computer program. The program performs the analysis using constant dollars and excludes general inflation. The MAP analysis uses a discount rate, the rate of interest reflecting the time value of money, of 4.6 percent from the Energy Prices and Discount Factors for Life-Cycle Cost Analysis 1992 manual published by the National Bureau of Standards (28:1). The MAP uses the utility escalation rates provided in the program by the Department of Energy.

Results of the Economic Analysis

A life cycle cost analysis determines the MAP recommendations for package units, reciprocating chillers, and centrifugal chillers. As stated previously, there are other considerations which may lead a manager to choose another alternative besides the most economical. Appendix B tabulates all of the data associated with the life cycle cost analysis performed on the equipment categories of the MAP. Table 5 summarizes the conclusions of the analysis.

Package Units. The economic analyses of all sizes of package units showed that maintaining the existing system realized the least annual cost. (The data is contained in Table 8 in Appendix B.) Since the Air Force wants to eliminate CFC use by 2000, the replacement for package units is new non-CFC package units.

Reciprocating Chillers. The results of the TLCC analyses for reciprocating chillers also showed that maintaining the existing systems yielded the least annual cost over the life of the equipment. (The data is contained in Table 9 in Appendix B.) However, when CFC use is banned, the TLCC shows two different results. From 25 up to 150 ton units, the replacement for reciprocating chillers is with a new non-CFC containing reciprocating chiller. For units from 150 to 200 tons, the replacement is with a new screw chiller.

TABLE 5

FINDINGS OF LIFE CYCLE COST ANALYSES

EQUIPMENT CATEGORY	RECOMMENDATIONS
RECIPROCATING PACKAGE UNITS	1. Maintain existing system.
(All Sizes)	2. When faced with mandatory phaseout, replace with new non-CFC reciprocating unit.
RECIPROCATING CHILLERS	1. Maintain existing system.
System Size	2. When faced with mandatory phaseout, replace with:
< 150 tons	a. new reciprocating chiller
≥ 150 tons	b. new screw chiller.
CENTRIFUGAL CHILLERS	1. Maintain existing system.
System Size	2. When faced with mandatory phaseout retrofit with non-CFC if system is:
200 tons	a. 11 years old or newer
400 tons	b. 17 years old or newer
1000 tons	c. 18 years old or newer
System Size	3. If system is older than optimum retrofit age above replace with:
200 tons	a. new screw chiller
400 tons	b. new centrifugal chiller
1000 tons	c. new centrifugal chiller

Centrifugal Chillers. The results of the TLCC analysis showed that maintaining existing centrifugal chillers is the least annual cost.

(The data is contained in Table 10 in Appendix B.) As with the other CFC refrigerant containing equipment, the units must be converted to non-CFC refrigerant equipment by 2000. When the unit is converted, a number of alternatives must be considered.

Retrofitting is the least cost non-CFC refrigerant alternative in all sizes of centrifugal chillers. The age of the existing equipment will determine the break-even point between a retrofit action and a replacement with new equipment. If a 200-ton chiller is 11 years old or less, a 400-ton chiller is 17 years old or less, or a 1000-ton chiller is 18 years old or less, the TLCC shows to retrofit the unit. The TLCC shows that a 200-ton to 400-ton centrifugal chiller beyond the retrofit age should be replaced with a screw chiller. The TLCC shows that centrifugal chillers over 400 tons and beyond the retrofit age should be replaced with a new centrifugal chiller.

V. Conclusions and Recommendations

The model action plan is designed to guide and aid a manager through the decision process of replacing air-conditioning and refrigeration equipment which use CFC refrigerants. This action is required by legislation since CFCs have been linked with stratospheric ozone depletion. This thesis process reviewed the applicable directives, researched containment methods, identified replacement refrigerants, and reviewed alternative processes. The model action plan provides a methodology for determining the most economical alternative and makes recommendations for actions to reduce the use of CFC refrigerants.

Conclusions

In accordance with AFR 19-15, all CFC refrigerants must be replaced by the year 2000. The ability to fund the replacement of the equipment or refrigerants will become of greater concern as the phaseout deadline draws closer. The thesis identifies the practical alternatives available and the approximate relative costs for each alternative. This information gives a manager the required information to plan and decide how to gradually phase out CFCs. The plan also provides the information to determine if current funding limits are adequate to achieve the replacement goals by 2000.

Directives. This plan is based on the current extent of published laws, regulations, and policies at the time of research. The EPA regulations based on Title VI on the CAAA have not been published yet. Air Force policy on CFCs has changed during the research effort and is likely to change more in the near future. This current uncertainty about the phaseout milestones will affect future decisions about CFC replacements. The MAP must be continually updated as new regulations and policies are developed.

Replacement Refrigerants. The literature search identified the non-CFC replacements for the CFC refrigerants currently in use at Air Force installations. The process of developing new refrigerants is ongoing in the hopes to adequately replace CFCs. However, the current replacements are less efficient and will require continued development of new and more efficient refrigerant and compression processes. Managers must also be aware and plan for the replacement of those systems using HCFC refrigerants, an interim CFC solution, as the regulatory phaseout milestones get closer.

Alternative Processes. Currently, absorption systems are not an economically competitive alternative because they require higher maintenance and investment costs. The advantage of absorption systems is they pose no harmful environmental effects. Future development and refinement of alternate processes like absorption systems may make them an economical solution in the future.

Economic Analysis. The life cycle cost analysis performed in the MAP was an effective method of selecting the best alternative. Since the replacement of air-conditioning and refrigeration equipment containing CFCs is dependent on funding, it is appropriate to select or recommend the best alternative based on cost.

As expected, the least annual cost alternative was to maintain the operation of the existing equipment through recovery and reuse of CFCs.

No required initial investment is the reason for the least cost. An advantage to maintaining existing equipment is cost savings. Another advantage is that by postponing equipment change-out, new equipment and refrigerants may become available that are superior to those now available.

A complete replacement of CFC containing equipment is required by the year 2000, so a systematic conversion is required to spread the cost over the phaseout period. CFC containing package units should be replaced with non-CFC package units. The most economical replacements for chillers are screw chillers. Because of the limited sizes of screw chillers, smaller reciprocating chillers should be replaced with new reciprocating chillers and larger centrifugal chillers should be replaced with new centrifugal chillers. A manager must include the factors of age, existing equipment condition, and critical cooling areas when prioritizing the CFC equipment for replacement.

Recommendations for Follow-On Research

Recommendations for further work focuses on three areas. The first is the development of a decision support system. The second is a field test of the MAP. Finally, develop a plan to reduce other ozone layer depleting substances used in the Air Force.

Decision Support System. Develop a computer based decision support system which would adopt a similar methodology to determine the best replacement alternative. The system must be capable of incorporating changes in directives, replacements, and alternate processes as they develop. The system should be able to incorporate cost changes for different areas. It might incorporate the maintenance and repair history of the existing equipment as a decision factor.

MAP for OLDS. Research a plan to reduce other OLDS used by the Air Force, such as halons for fire suppression and solvents for cleaning. Since halon is the main fire suppression agent used to protect computer rooms and aircraft, it is important that a suitable substitute be found. Development of alternatives for halons continues and research may uncover a direction for future fire suppression. A plan to reduce CFC solvents used in aircraft maintenance will complement the plan to reduce the use of CFC refrigerants to be in compliance with the CFC phaseout. MAP Field Test. The first recommendation is to field test the MAP. This would include using the MAP at an Air Force base and developing a long term plan to reduce CFC refrigerants. This may identify additional requirements needed by managers and modifications of the MAP would make it an even better tool for air-conditioning and refrigeration systems managers.

Appendix A: Model Action Plan

The purpose of this model action plan (MAP) is two-fold. First, it is a management aid for managers of air-conditioning and refrigeration systems. The MAP is a guide to determining what practical alternatives are available when forced to reduce the use of CFCs. The MAP also makes a general recommendation for the most cost-effective alternative. Second, the MAP enables a manager to perform an evaluation of alternatives for a specific case. The MAP provides the details for conducting an economic analysis to evaluate specific applications.

The MAP is divided into three parts. The first part contains a list of practical alternatives when faced with deciding to eliminate a CFC refrigerant system. Next is a section containing step by step instructions on how to evaluate alternatives using a life cycle cost economic analysis. The last part of the MAP makes recommendations based on life cycle cost analyses of a model application.

Practical Alternatives

Table 6 contains a list of practical alternatives for each category of air conditioning and refrigeration systems. Reciprocating package units is a category that includes unitary and packaged terminal air conditioners and heat pumps, room air conditioners, and dehumidifiers. This category also applies to refrigeration systems from appliances to commercial units. The categories of reciprocating and centrifugal chillers includes air conditioning and refrigeration systems with reciprocating and centrifugal compressors, respectively.

TABLE 6

LIST OF PRACTICAL ALTERNATIVES

CFC-Based System	Practical Alternatives
Reciprocating Package Units or Rotary Compressor Units	Maintain existing system Change out with new HFC-134a system Change out with new absorption system Change out with new HCFC-22 system
Reciprocating Chillers	Maintain existing system Change out with new HFC-134a system Change out with new absorption system Change out with new HCFC-22 system
Centrifugal Chillers	Maintain existing system Retrofit CFC-11 system with HCFC-123 Retrofit CFC-12 system with HFC-134a Change out with new absorption system Change out with new HCFC-22
Automotive Air Conditioners	Maintain existing system Change out with new HFC-134a system

The alternatives listed have been selected as practical for typical applications based on current information regarding equipment and refrigerant availability, compatibility, and safety. Other alternatives considered undesirable due to inferior performance or hazardous materials are not listed. Though it is possible to retrofit some reciprocating chillers, the associated loss of efficiency and cooling capacity is significant. Therefore, the MAP does not consider retrofitting a practical alternative. Some alternatives listed may not be appropriate for all situations. Maintaining existing CFC systems is only feasible until their use is abandoned because of regulated phaseout. Figure 5 is a decision diagram to help eliminate inappropriate alternatives.

General Recommendations

Table 7 contains recommended courses of action for general air-conditioning and refrigeration categories. The recommendations are based on economic analyses using total life cycle costs for a model application. In the model, replacement costs and immediate salvage value were assumed to be zero. The analysis used a 4.6 percent discount rate in accordance with the Energy Prices and Discount Factors for Life-Cycle Cost Analysis 1992 manual published by the National Bureau of Standards (28:1). In order to cover a broad spectrum of air-conditioning and refrigeration applications, the model was not based on a specific building or application. As a result, certain assumptions were made when estimating energy consumption. Actual values should be used when figuring energy use for a specific application.

The model uses cost and weather data for the Dayton, Ohio area. Cost data were obtained from a cost estimating guide. The model assumed that the systems were perfectly sized for the heat load. The model assumed a 75°F indoor cooling temperature and a 55°F cooling balance temperature. Other values used in the analysis include 1036 cooling degree-days, and a five percent duct loss factor.

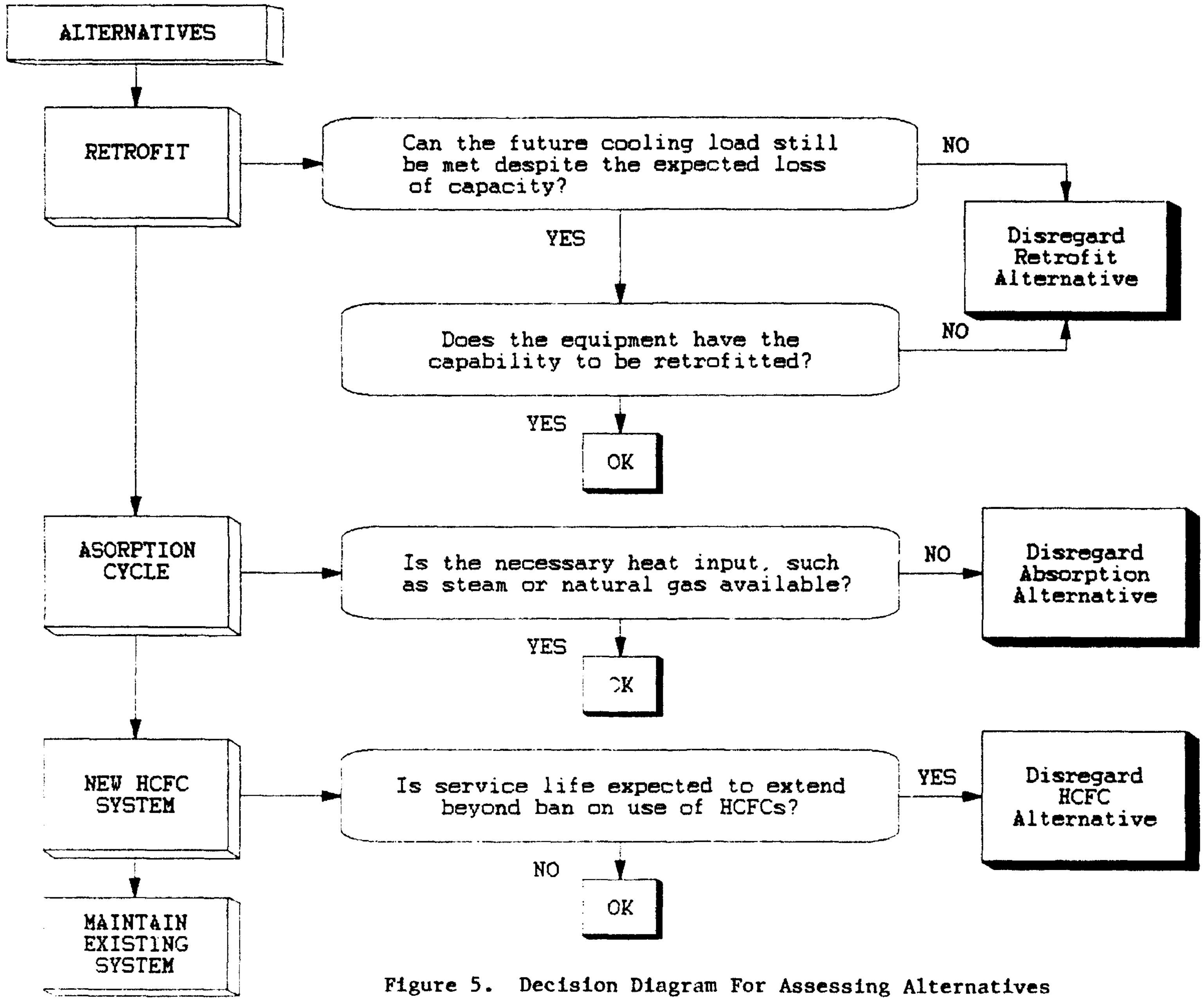

Figure 5. Decision Diagram For Assessing Alternatives

TABLE 7

TABLE OF RECOMMENDATIONS

EQUIPMENT CATEGORY	RECOMMENDATIONS
RECIPROCATING PACKAGE UNITS	1. Maintain existing system.
(All Sizes)	2. When faced with mandatory phaseout, replace with new non-CFC reciprocating unit.
RECIPROCATING CHILLERS	1. Maintain existing system.
System Size	2. When faced with mandatory phaseout, replace with:
< 150 tons	a. new reciprocating chiller
≥ 150 tons	b. new screw chiller.
CENTRIFUGAL CHILLERS	1. Maintain existing system.
System Size	2. When faced with mandatory phaseout retrofit with non-CFC if system is:
200 tons	a. 11 years old or newer
400 tons	b. 17 years old or newer
1000 tons	c. 18 years old or newer
System Size	3. If system is older than optimum retrofit age above replace with:
200 tons	a. new screw chiller
400 tons	b. new centrifugal chiller
1000 tons	c. new centrifugal chiller

Total Life Cycle Cost Analysis

The following is a step by step procedure to evaluate alternatives using a total life cycle cost analysis. All system costs are expressed in terms of annual costs over the life of the system. A cooling load calculation manual or program is recommended for reference purposes.

Step 1. Estimate Investment Cost (I)

What is the sum of costs for new equipment, parts, materials, and installation?

Step 2. Estimate Salvage Value (S)

What value does the system have at the end of its life cycle? (Salvage value is assumed to be zero unless the system can actually be sold for a price or used in a different application.)

Step 3. Estimate Operations and Maintenance Costs (M)

What is the sum of costs for annual recurring costs (such as periodic maintenance) and non-annual recurring costs (such as scheduled overhauls)?

Step 4. Estimate Energy Costs (E)

Estimate annual cost from energy consumption of the system using any accepted method. The following process is offered as a suggestion:

4.1. What is the system's average coefficient of performance (COP)? The COP is a dimensionless quantity and may be obtained from the equipment specifications. The COP should be adjusted for the loading to obtain an average value. Refer to the energy estimating section of the ASHRAE Handbook, Fundamentals on how to do this (5:28.7).

4.2. What is the number of cooling degree-days (CDD) for the location? The units for CDD should be in units of °F·days. Values of CDD may be found in Air Force Manual (AFM) 88-29. Cooling degree-days should be adjusted for the cooling balance temperature. Again, refer to the energy estimating section of the ASHRAE Handbook, Fundamentals on how to do this (5:28.7).

4.3. Estimate the duct loss factor (DLF). The DLF is the heat energy lost through the air supply ducts expressed as a percent of total energy. You may assume an average DLF of 0.05 for most systems.

4.4. Calculate the building loss coefficient (BLC). The BLC should be expressed in units of Btu/h·°F, and is calculated as follows:

4.4.1. Estimate the building heat transfer coefficients (U) in units of Btu/h·ft^2·°F, and area (A) in square feet for walls (W), roofs (R), and floors (F), U_w, U_r, U_f, A_w, A_r, and A_f, respectively.

4.4.2. Estimate the heat loss due to infiltration (I) in units of Btu/h·°F.

4.4.3. $BLC = I + (U_w * A_w + U_r * A_r + U_f * A_f)$

4.5. Calculate annual energy consumption (E_c) in units of Btu/yr with the equation $E_c = 24 * BLC * CDD * (1 + DLF) / COP$.

4.6. What is the cost of energy (COE) in units of dollars/Btu? (1 kilowatt·hour = 3412 Btu)

4.7. $E = E_c * COE$

Step 5. Calculate total life cycle cost (TLCC) as follows:

$$TLCC = I - S + M + E$$

Step 6. Repeat steps 1 through 5 for each alternative.

Step 7. Select alternative with the least TLCC.

The equivalent uniform annual cost method may be used to compare alternatives on an equivalent basis since equipment service lives may be different. To obtain annual equivalent amounts from future values, the future values are first converted to present equivalent amounts using the equation (23:56):

$$PE = F / (1 + i)^{t}$$

where

PE = present equivalent amount
F = future amount
i = discount rate (percent)
t = number of years from the present

Annual equivalent amounts are then calculated using the equation (23:56):

$$AE = PE * \{ i*(1 + i)^{n} / [(1 + i)^{n} - 1] \}$$

where

AE = annual equivalent amount
PE = present equivalent amount
i = discount rate (percent)
n = number of years in the life cycle

Appendix B: Compilation of Cost Data Tables

This appendix contains tables of data used in performing life cycle cost analyses and the output from those analyses.

Table 8.

Table 8 contains data from total life cycle cost analyses of package reciprocating air-conditioning and refrigeration systems in sizes from 5 to 50 tons. The column labeled "Annual LCC" is the output from the Building Life Cycle Cost computer program. The values shown for annual life cycle cost of existing equipment are average costs taken from the range in equipment life. At no time was the annual life cycle cost of the existing equipment more costly than that of the new system.

TABLE 8

LIFE CYCLE COST (LCC) ANALYSIS FOR RECIPROCATING PACKAGE UNITS

Cooling Size (Tons)	ALTERNATIVE	Service Life (Yrs)	Invest Cost ($)	Annual O&M Cost ($)	Non-Rec O&M Cost ($)	Energy Cost ($)	Annual LCC ($)
5	Existing Equipment	1-15	0	445	1500	378	1080
	New R-22/134a (Pack)	15	5601	445	1500	378	1554
10	Existing Equipment	1-15	0	760	2575	756	1950
	New R-22/134a (Pack)	15	9498	760	2575	756	2761
25	Existing Package	1-15	0	1405	4780	1890	4125
	New R-22/134a (Pack)	15	17231	1405	4780	1890	5573
50	Existing Package	1-15	0	2500	8500	3781	7750
	New R-22/134a (Pack)	15	30593	2500	8500	3781	10330

TABLE 8 (Cont.)

Cooling Size (Tons)	ALTERNATIVE	Initial Cost ($)	Demo Cost ($)	BLC (Btu/h*F)	COP	Energy (Btu)	Energy (kWh)
5	Existing Equipment	0	0	3000	2.55	3.1E+07	9002
	New R-22/134a (Pack)	5235	366	3000	2.55	3.1E+07	9002
10	Existing Equipment	0	0	6000	2.55	6.1E+07	18004
	New R-22/134a (Pack)	8897	601	6000	2.55	6.1E+07	18004
25	Existing Package	0	0	15000	2.55	1.5E+08	45009
	New R-22/134a (Pack)	16526	704	15000	2.55	1.5E+08	45009
50	Existing Package	0	0	30000	2.55	3.1E+08	90019
	New R-22/134a (Pack)	29391	1202	30000	2.55	3.1E+08	90019

NOTE: CCD is 1036 F-Days and DLF is 0.05 for all alternatives.

Table 9.

Table 9 contains data from total life cycle cost analyses of reciprocating chiller systems ranging in sizes from 25 tons to 200 tons. Values in the "Annual LCC" column are output from the Building Life Cycle Cost computer program. The values of annual life cycle cost for the existing system are an average over the equipment service life. For no year throughout the service life were the existing system annual life cycle costs higher than that of the other alternatives listed.

TABLE 9

LIFE CYCLE COST (LCC) ANALYSIS FOR RECIPROCATING CHILLERS

Cooling Size (Tons)	ALTERNATIVE	Service Life (Yrs)	Invest Cost	Annual O&M Cost	Non-Rec O&M Cost (5, 10, 15)	Non-Rec O&M Cost (10, 20)	Energy Cost	Annual LCC
25	Existing Chiller	1-20	0	2000	6800		1205	4400
	New R-22/134a (Chiller)	20	22273	2000	6800		1205	5979
	New Absorption (Gas)	23	27762	3140		12500	1547	8006
50	Existing Chiller	1-20	0	2500	8500		2410	6400
	New R-22/134a (Chiller)	20	35982	2500	8500		2410	9025
	New Absorption (Gas)	23	56387	3925		25000	3094	13719
75	Existing Chiller	1-20	0	3000	1200		3615	8400
	New R-22/134a (Chiller)	20	52875	3000	10200		3615	12318
	New Absorption (Gas)	23	84566	4710		38000	4641	18652
100	Existing Chiller	1-20	0	3500	11900		4820	10500
	New R-22/134a (Chiller)	20	67021	3500	11900		4820	15397
	New Absorption (Steam)	23	105426	5495		48000	6187	30969
150	Existing Chiller	1-20	0	4000	13600		7231	13600
	New R-22 Chiller	20	100919	4000	13600		7231	21235
	New Absorption (Steam)	23	136132	6280		62000	9281	40148
	New Screw	23	90889	4000	12600		6357	17996
200	Existing Chiller	1-20	0	4500	15300		9641	16900
	New R-22 Chiller	20	131263	4500	15300		9641	26797
	New Absorption (Steam)	23	154738	7065		24021	12375	49699
	New Screw	23	105850	4500	15000		8476	21926

TABLE 9 (Cont.)

Cooling Size (Tons)	ALTERNATIVE	Install Cost	Demo Cost	BLC (Btu/h°F)	COP	Energy (Btu)	Energy (kWh)	Energy (CCF)
25	Existing Chiller	0	0	15000	4	9.79E+07	28693	
	New R-22/134a (Chiller)	20404	1869	15000	4	9.79E+07	28693	
	New Absorption (Gas)	25893	1869	15000	1	3.92E+08		3916
50	Existing Chiller	0	0	30000	4	1.96E+08	57387	
	New R-22/134a (Chiller)	32649	3333	30000	4	1.96E+08	57387	
	New Absorption (Gas)	53054	3333	30000	1	7.83E+08		7832
75	Existing Chiller	0	0	45000	4	2.94E+08	86080	
	New R-22/134a (Chiller)	47889	4986	45000	4	2.94E+08	86080	
	New Absorption (Gas)	79580	4986	45000	1	1.17E+09		11748
100	Existing Chiller	0	0	60000	4	3.92E+08	114774	
	New R-22/134a (Chiller)	61035	5986	60000	4	3.92E+08	114774	
	New Absorption (Steam)	99440	5986	60000	1	1.57E+09		15664
150	Existing Chiller	0	0	90000	4	5.87E+08	172161	
	New R-22 Chiller	93431	7489	90000	4	5.87E+08	172161	
	New Absorption (Steam)	128643	7489	90000	1	2.35E+09		23496
	New Screw	83400	7489	90000	4.55	5.16E+08	151350	
200	Existing Chiller	0	0	120000	4	7.83E+08	229547	
	New R-22 Chiller	119253	12010	120000	4	7.83E+08	229547	
	New Absorption (Steam)	142728	12010	120000	1	3.13E+09		31329
	New Screw	93840	12010	120000	4.55	6.89E+08	201800	

NOTE: Cooling degree days (CDD) is 1036 F-days, and duct loss factor (DLF) is 0.05 for all alternatives.
All costs shown are in dollars.

Table 10.

Table 10 contains data from total life cycle cost analyses of centrifugal chiller systems ranging in sizes from 200 to 1000 tons. In these analyses the total life cycle costs of the existing system exceeded that of at least one other alternative over part of the range of equipment age. Output values from the Building Life Cycle Cost computer program over the range of equipment life are contained in Table 11.

TABLE 10

LIFE CYCLE COST (LCC) ANALYSIS FOR CENTRIFUGAL CHILLERS

Cooling Capacity (Tons)	ALTERNATIVE	Service Life (Yr)	Invest Cost	Annual O&M Cost	Non-Rec O&M Cost (5, 15)	Non-Rec O&M Cost (10, 20)	Energy Cost	Annual LCC
200	Existing R-11/12 System	1-23	0	4500	2500	45000	6766	NOTE 1
	Retrofit Existing System	1-23	65000	4500	2500	45000	6766	NOTE 1
	New Packaged Hermetic	23	117657	4500	2500	45000	6766	23398
	Absorption (Steam)	23	158973	7065	0	70650	23121	50292
	New Screw	23	110085	4500	1000	15000	8476	22229
400	Existing R-11/12 System	1-23	0	6230	3000	53000	13531	NOTE 1
	Retrofit Existing System	1-23	73000	6230	3000	53000	13531	NOTE 1
	New Hermetic	23	162776	6230	3000	53000	13531	35904
	Absorption (Steam)	23	242591	9781	0	83210	46241	86539
	New Screw	23	157275	6230	1500	20760	16951	36462
1000	Existing R-11/12 System	1-23	0	5950	3700	74000	33828	NOTE 1
	Retrofit Existing System	1-23	94000	5950	3700	74000	33828	NOTE 1
	New Hermetic	23	280489	5950	3700	74000	33828	66393
	Absorption (Steam)	23	441997	9342	0	116180	115603	181821
	New Screw	23	336896	5950	2500	56520	42378	77743

NOTE 1. Data contained in Table 11

TABLE 10 (Cont.)

Cooling Capacity (Tons)	ALTERNATIVE	Initial Cost	Demo Cost	BLC (Btu/h*F)	COP	Energy (Btu)	Energy (kWh)
200	Existing R-11/12 System	0	0	120000	5.7	5.50E+08	161086
	Retrofit Existing System	65000	0	120000	5.7	5.50E+08	161086
	New Packaged Hermetic	101412	16245	120000	5.7	5.50E+08	161086
	Absorption (Steam)	142728	16245	120000	1	3.13E+09	
	New Screw	93840	16245	120000	4.55	6.89E+08	201800
400	Existing R-11/12 System	0	0	240000	5.7	1.10E+09	322172
	Retrofit Existing System	73000	0	240000	5.7	1.10E+09	322172
	New Hermetic	140381	22395	240000	5.7	1.10E+09	322172
	Absorption (Steam)	220196	22395	240000	1	6.27E+09	
	New Screw	134880	22395	240000	4.55	1.38E+09	403600
1000	Existing R-11/12 System	0	0	600000	5.7	2.75E+09	805430
	Retrofit Existing System	85000	0	600000	5.7	2.75E+09	805430
	New Hermetic	241793	38696	600000	5.7	2.75E+09	805430
	Absorption (Steam)	403301	38696	600000	1	1.57E+10	
	New Screw	298200	38696	600000	4.55	3.44E+09	1009000

NOTE 2. Cooling degree days (CDD) is 1036 F-days and duct loss factor (DLF) is 0.05 for all alternatives.

NOTE 3. All costs shown are in dollars.

Table 11.

Table 11 contains output data from the Building Life Cycle Cost computer program for 200, 400, and 1000-ton centrifugal chillers. The input values for the program are given in Table B.3. The analyses were run for existing equipment aged from one to twenty years. The cost to retrofit a 200-ton system is the least costly alternative through age eleven. After eleven years, a new screw chiller provides the least cost. Figure 6 shows this information graphically.

For a 400-ton centrifugal chiller, a new screw or centrifugal chiller is less expensive than retrofitting when the existing equipment is over 17 years old. This break-even point can be seen in Figure 7. For 1000-ton systems, it becomes more cost-effective to change to a centrifugal system when the existing system is older than 18 years, as can be seen in Figure 8.

TABLE 11

LIFE CYCLE COSTS FOR CENTRIFUGAL CHILLERS

AGE (Years)	200-Tons EXISTING ($)	200-Tons RETROFIT ($)	400-Tons EXISTING ($)	400-Tons RETROFIT ($)	1,000-Ton EXISTING ($)	1,000-Ton RETROFIT ($)
1	15,324	19,966	24,579	29,724	46,373	52,017
2						
3	15,846	20,323	25,259	30,256	47,656	52,599
4						
5						
6						
7						
8	17,818	20,423	27,536	30,274	50,743	52,414
9						
10		21,256		31,202		
11		21,863				
12		22,590				56,987
13	15,779	23,470	25,134	33,731	47,320	56,466
14		20,587		30,306		
15		21,542				53,552
16		22,774		32,798		
17		24,427		34,687		
18	20,836	26,745	31,177	37,334	56,103	62,801
19		29,612		40,528		66,969
20		35,120		46,697		74,864

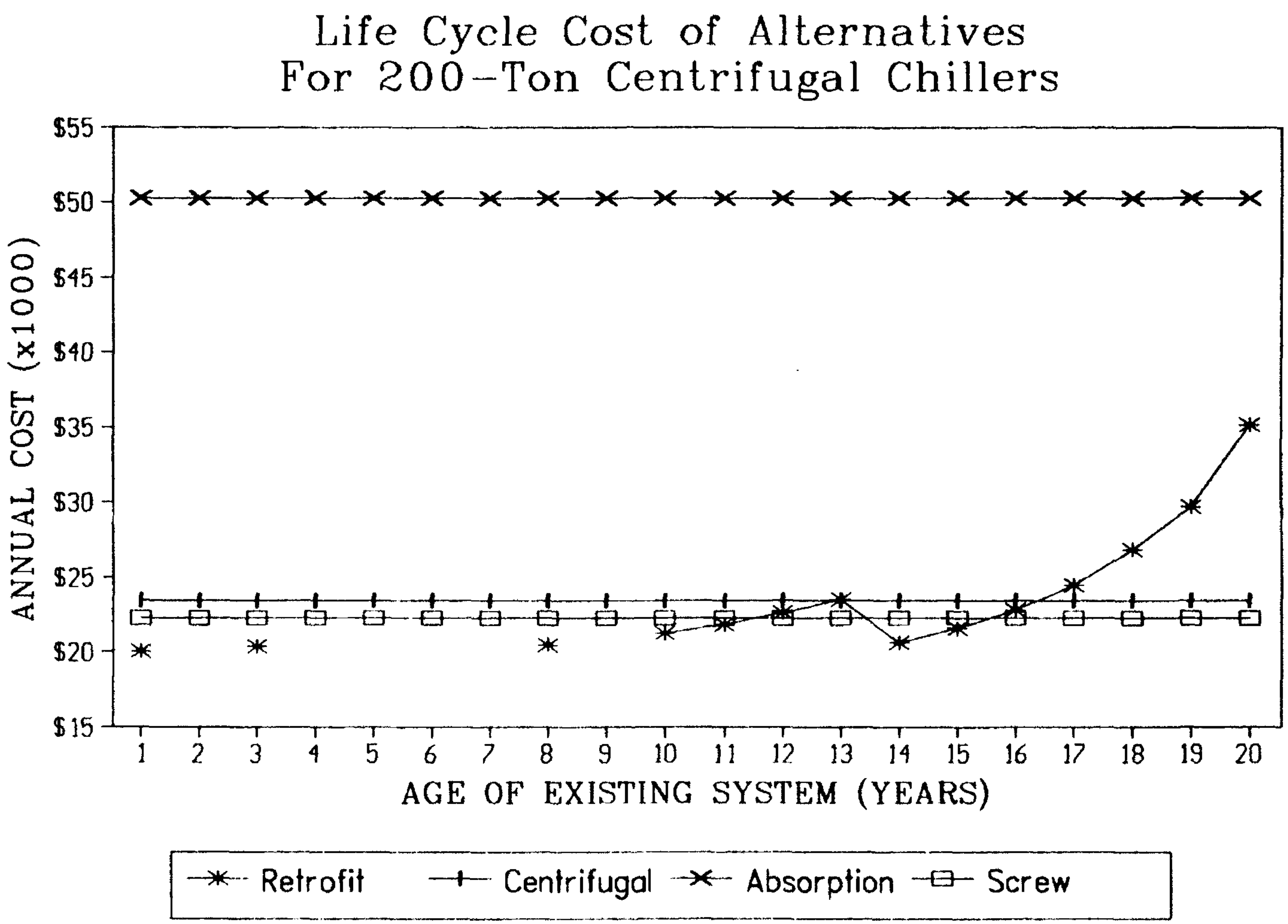

Figure 6. Life Cycle Cost of Alternatives For 200-Ton Centrifugal Chillers

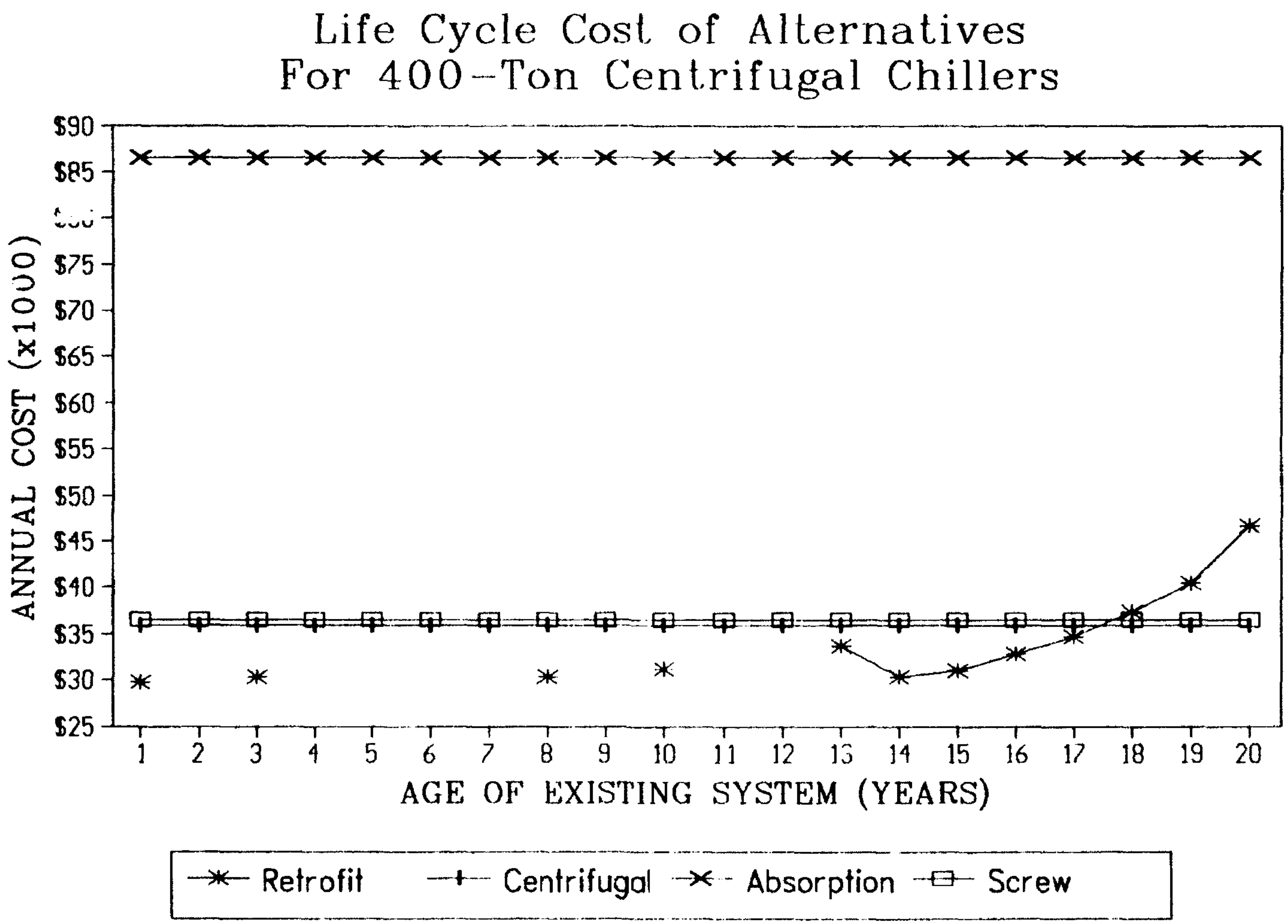

Figure 7. Life Cycle Cost of Alternatives For 400-Ton Centrifugal Chillers

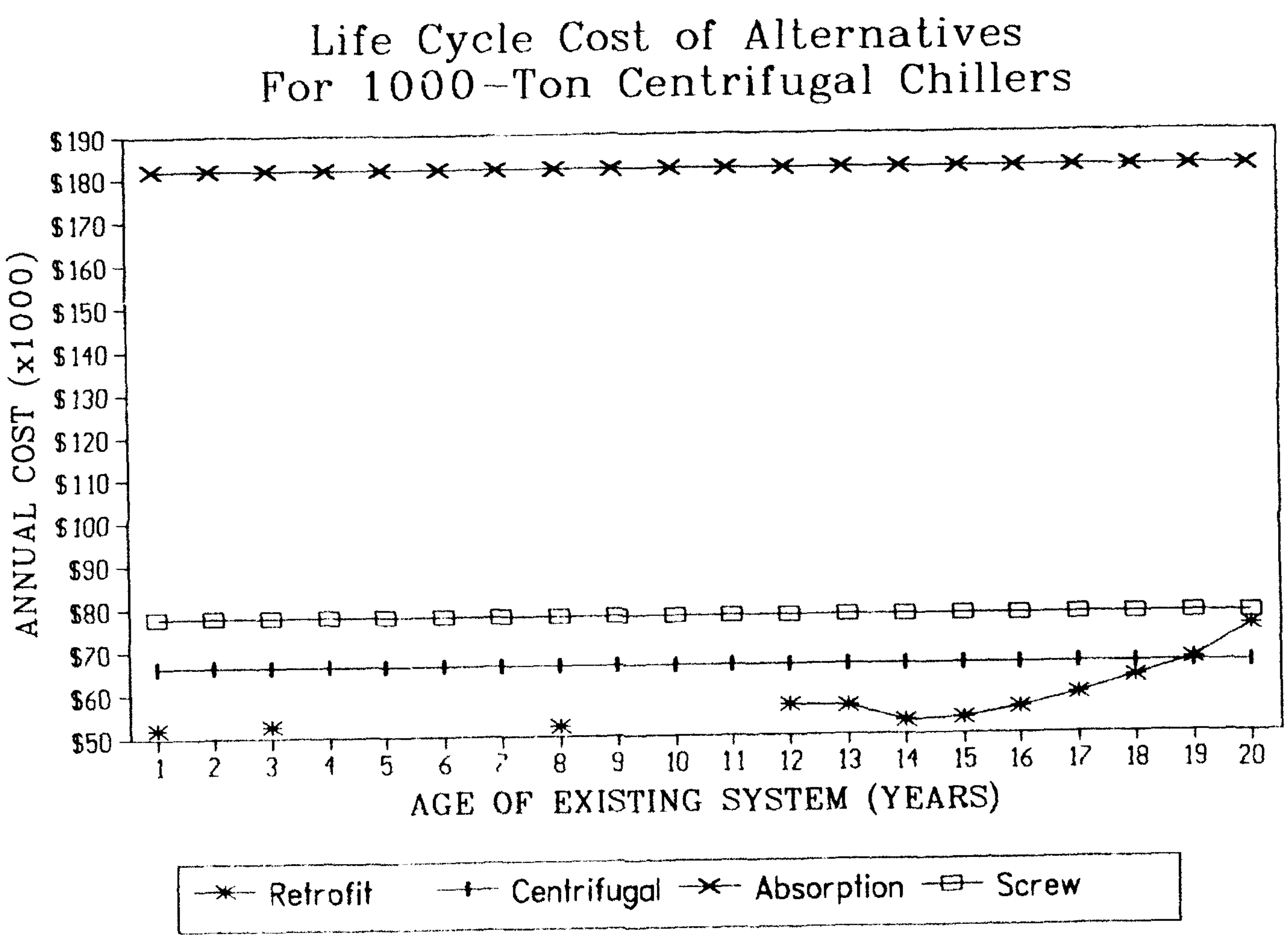

Figure 8. Life Cycle Cost of Alternatives For 1000-Ton Centrifugal Chillers

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Vitae

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13. ABSTRACT *(Maximum 200 words)*

This study investigated methods to reduce the use and release of chlorofluorocarbon (CFC) refrigerants and evaluated alternatives to CFCs in air-conditioning and refrigeration systems. A life cycle cost (LCC) analysis formed the basis for evaluation. A literature review examined applicable CFC directives, containment methods, replacement refrigerants, and alternative processes. The results of the LCC analysis showed that maintaining the existing CFC system was always the least costly alternative. When forced to replace a CFC reciprocating package unit, the best replacement was a non-CFC reciprocating unit. The most practical replacement for reciprocating chillers was a new reciprocating chiller for systems less than 150 tons, and screw chillers for systems 150 tons or larger. Retrofitting a centrifugal chiller was cost-effective if the system had been in service no more than 11 years for a 200-ton unit, 17 years for a 400-ton unit, and 18 years for a 1000-ton unit. Otherwise, 200-ton units should be replaced with screw chillers and 400 and 1000-ton units with centrifugal chillers.

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